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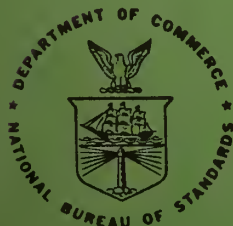
Field Performance of Residential Refrigerators and Combination Refrigerator-Freezers

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ABSTRACT

Evaluation of the performance of household refrigerators and combination refrigerator-freezers was undertaken in a field experiment to determine the effect of room environment and occupant-usage habits on energy consumption of these appliances. This report presents the results of such an experiment on ten townhouses at Twin Rivers, N.J. One-door manual defrost and two-door frost-free models of various sizes were studied. Energy consumption, kitchen temperature, refrigerator temperature and door openings were measured for each model by data acquisition systems located in the townhouse basements. Both daily and hourly averages and variations about the average for each variable were calculated in order to determine the occupant-usage patterns.

Statistical techniques were utilized to obtain the effect of parameters on energy consumption of these appliances by linear regression of both one- and two-parameter models.

It was found that for a given model the temperature difference between the kitchen and the refrigerator (either main or freezer section) had the most effect on energy consumption, with a lesser, though still important, contribution from the door openings.

In addition, the normalized energy consumption of each model, in different combinations of variables, was calculated from its regression coefficients and the overall average values of parameters from measurements. The results of these normalized values turned out to be within 5%. Therefore, their mean values could be considered as the typical energy consumption for each refrigerator or combination, under usage conditions.

The linear relationship among the combination refrigerator-freezers according to their physical sizes indicated an increase of about 0.55 kWh per day for each additional cubic foot increase in volume. Energy conservation by using a manual-defrost refrigerator was predicted at approximately 40% of that of a frost-free model.

Key Words: Combination refrigerator-freezer field data; daily load profiles; energy consumption; field measurements; hourly load profiles; refrigerator field data; usage profiles.

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FIELD PERFORMANCE OF RESIDENTIAL REFRIGERATORS
AND COMBINATION REFRIGERATOR-FREEZERS

Yui-May L. Chang and Richard A. Grot

1. INTRODUCTION

A field experiment* was undertaken in ten townhouses at Twin Rivers,
N.J. to determine the occupant-controlled parameters which can affect
the energy consumption of a household refrigerator** and to assist in
a realistic appliance labeling program for evaluation of household
refrigerators.

The site of Twin Rivers, N.J. was selected due to the previous exten-
sive investigations on energy usage at that site by researchers at
Princeton University [1,2]. The ten townhouses in this study were
selected on the basis of their previous energy usage data. The object
was to obtain, in a small sample, a distribution which reflected the
energy usage of the population of Twin Rivers. The refrigerators
studied were those already in the townhouses, either supplied by the
developer or purchased separately by the occupants. The refrigerators
in these townhouses were a one-door manual defrost and nine two-door
frost-free models of various sizes, including one side-by-side model.
The physical characteristics of the refrigerators in each town-house
are given in Table 1. The occupants were mostly typical families
containing two adults and one to three children, ages from 1 to 15
years old. A summary of occupants in each townhouse is given in
Table 2.

Instrumentation was installed in each townhouse so that the energy
usage of the refrigerator, the kitchen temperature, the refrigerator
main-section temperature, the refrigerator freezer-section temperature,
the number and duration of openings of the main section door, and the
number and duration of openings of the freezer section door were
recorded. Figure 1 is a schematic of the instrumentation. After the
completion of instrumentation, data collection was begun in April 1976.
The electric energy use of the refrigerator was measured by installing
an electric meter modified so that a pulse was generated for each 1.8
watt-hours of electricity. The pulses from the electric meter were
summed by a specially designed electronic counter which produced an
analogue signal proportional to the total number of pulses. The opening

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**Refrigerator, as used in this report, refers to refrigerators as well
as combination refrigerator-freezer.

of the main section and freezer section doors were determined by placing small magnets and miniature magnetic reed switches on the door and refrigerator so that each time the door was opened or closed the magnetic reed switch would open or close. These signals were fed into an encoder card which produced an analogue signal from which the status of the door positions could be determined (i.e., whether the door was open or closed). The computer analysis determined the number and duration of door openings.

The encoder also generated a parity signal which changed state whenever the status of the encoded events changed. This means, for example, that when the refrigerator door was opened from closed position, or closed from the open position. The scan control card would generate a pulse which would in turn cause a scan of the data acquisition. From these event scans, the number and duration of each door opening could be determined. The temperatures in the kitchen and refrigerator, both main and freezer sections were measured with T-type thermocouples. The kitchen temperature thermocouple was located above the kitchen sink. The refrigerator main section temperature thermocouple was attached to a center shelf at the rear of the refrigerator. The thermocouple in the freezer section was located at the rear of the freezer section. Since the refrigerators were in use by the occupants, these locations were dictated by the circumstances. It would have been impossible to locate these thermocouples according to the standard test procedures by AHAM and ASHRAE [3,4].

The instrumentation was installed so that one data acquisition system would monitor a pair of townhouses. Townhouses #1 and #2 shared the same data acquisition system; likewise, townhouses #3 and #4, . . . etc. For each pair of townhouses, the data acquisition system would scan and record measurements of the HVAC system, appliances and room environment periodically once every five minutes on a seven-track incremental magnetic tape recorder. In addition, it also recorded the event actuated scans caused by the opening and closing of the refrigerator doors. It took about six seconds to scan all channels of data. There are approximately 4500 scans on each tape, which is equivalent to seven days of data. The tapes were changed once a week and shipped to the National Bureau of Standards (NBS) by researchers at Princeton University, who also monitored the operation of the equipment.

The five-minute data were reduced on either the CBT minicomputer or the NBS central computer facility into daily and hourly data files, which were printed and stored on mass storage files for further analysis. The hourly data of all measurements were analyzed to obtain average hourly profiles by averaging measured values during each hour over a period of certain days. As for refrigerator door openings, only daily usage profiles were reduced from data, since hourly measurements were immaterial. The graphs presented in the report include actual measurements for four-day periods. From the graphical presentation of the four-day plots of internal temperature, the defrost cycle of each refrigerator can be observed.

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On the daily data summaries, statistical analyses were performed to obtain the variations from the average values and to determine the effect of usage parameters on energy consumption. According to these field measurements under actual usage conditions, the average daily energy consumption of various refrigerators was found to depend mainly on the size of the refrigerator, as expected. For a given refrigerator, the temperature difference between the kitchen and the refrigerator influenced the daily energy consumption of the refrigerator more than did the number or duration of the door openings. The average daily number of door openings for all refrigerators was found to be 48 for the main section and 10 for the freezer section. It was also interesting to learn that the average length of time per door opening for the two sections of these refrigerators turned out to be nearly the same, 21 seconds for the main section and 20 seconds for the freezer section. For all refrigerators, the average values of temperature differences between kithcen and the refrigerator, were calculated to be $\overline{\Delta T_M}$ = 42°F for the main section and $\overline{\Delta T_F}$ = 73.5°F, for the freezer section, with kitchens at an average temperature of 78.4°F. In order to study relationships among energy consumption, differential temperature between kitchen and refrigerators, and door openings, the least-squares estimation of linear regression with both single and multiple variant were used.

Simple performance equations (equations 1 and 2 in section 2.3) of the mathematical model for energy usage and its dependent variables were employed. From these equations and their calculated coefficients, the predicted value and the actual data value were plotted together to show their differences for each refrigerator. The energy consumptions of refrigerators of different sizes were compared by using the overall average values of temperature difference between kitchen and refrigerators, $\overline{\Delta T_M}$ and $\overline{\Delta T_F}$, and door openings.

2. GRAPHICAL AND ANALYTICAL REPRESENTATION OF MEASUREMENTS

2.1 ANALYSIS OF HOURLY DATA

The energy consumption and the usage pattern of the refrigerator in each household are presented as averages for each hour. Refrigerator in townhouse #8 is one of the six refrigerators for which a complete set of data is available and has been arbitrarily selected for presentation. The actual hourly energy consumption and temperatures of this refrigerator for a period of four days are shown in Figures 2, 3 and 4. From Figures 3 and 4, both main-section temperature and freezer-section temperature can be observed to have peaks at the same time. The refrigerator is controlled in an on-off manner by a single thermostatic switch, and the temperature controls of both sections depend on their control knobs as well as a damper to limit air flow between them. Time intervals between peaks in these two figures indicate the period of defrost cycles because, at the beginning of each defrost cycle, electric heat is applied to its evaporator to melt the frost [5].

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These two figures also show that this frost-free refrigerator has its defrost cycle occurring approximately every six hours. By studying all three graphs, Figures 2, 3, and 4, it could be seen that the hourly energy usage increases after the refrigerator self-defrosts, as the refrigerator temperature has to be reduced immediately.

Furthermore, the number and duration of door openings of the refrigerator, shown in Figure 5-8, change the refrigerator temperature patterns and therefore affect the energy usage indirectly. The periods of door openings relate directly to the number of door opening. It can also be noticed that the door openings are either zero or a very small number from midnight to 6:00 am., and the refrigerator's internal temperature remains pretty much the same, except when the defrost cycle comes on. Therefore, the hourly energy consumption at night is usually lower than at any time of the day. This is also due to the fact that the kitchen temperature is always fairly low at night, as shown in Figure 9.

Figure 10 is an average profile of energy consumption for each hour of the day, from days 96 to 180, of the refrigerator in townhouse #8. For Figures 10, 11 and 12 the solid area is the average energy used, and the dotted profile gives two standard deviations from the average.

In comparing Figures 2 and 10, the measurements of hourly energy consumption of the refrigerator for days 176-179 and the average hourly energy consumption profile for days 96-180 do not show much similarity. In fact, Figure 2 shows a slightly higher energy usage on those four days than the average hourly energy usage given in Figure 10 and Table 3. This might be due to the surprisingly high temperature in the kitchen on those four days as shown in Figure 9. Figure 9 indicates the kitchen temperatures from measurements are much higher than the daily average value of 77.6°F, given in Table 4.

Figure 10 shows that slightly more energy is used during lunch time and dinner time, when refrigerator doors are opened more frequently, as indicated in Figures 11 and 12. The actual variation of refrigerator energy used in townhouse #8 for each hour of the day is shown in the set of 24-hour frequency plots (Figures 13-16). Table 3 is a summary of these variations for each hour of the day in average energy consumption and door openings of all ten townhouses.

2.2 ANALYSIS OF THE DAILY PERFORMANCE

When a refrigerator is being operated normally, its daily energy usage does not vary greatly; however, those variations which do occur should indicate the effect of such parameters as kitchen temperature and door openings on the energy consumption of the refrigerator. Figure 17 is a plot of the daily energy consumption of the refrigerator of townhouse #8. The frequency plot in Figure 18 shows the energy usage of this refrigerator ranged from 4 kWh to 8 kWh per day, with a mean

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of 6.45 kWh per day. A summary of the daily performance of the refrigerators in these ten townhouses is given in Table 4. By referring to Tables 1 and 4, the dependence of the refrigerator average daily energy consumption on its physical size can be noted. The values vary from 2.30 kWh per day for the refrigerator in townhouse #3 (an 11.5 ft^3 one-door manual-defrost model) to 8.33 kWh per day for the refrigerator in townhouse #10 (a 19.0 ft^3 two-door side-by-side self-defrosted model). Note that even though the data days were different, the comparisons are still valid, since the average kitchen temperature, T_K, remained pretty much the same for each particular period of time, except for townhouse #3.

For those refrigerators with the same physical characteristics as shown in Table 1 (e.g., in townhouses #7 and #8) the temperature difference between kitchen and refrigerator dominates their energy usage, with small effects due to the door openings. Table 4 indicates that the differential temperature between kitchen and freezer in townhouse #8, 72.1°F, was much higher than in townhouse #7, 65.6°F, while their differential temperatures between kitchen and main section were kept approximately the same, 44.2°F and 44.7°F, respectively. This factor could explain why the refrigerator in townhouse #8 has a higher energy consumption than that in townhouse #7, as given in Table 4.

By sketching the refrigerator daily energy usage with temperature difference between kitchen and freezer of the refrigerator in townhouse #8, given in Figure 19, it can be noticed that the two curves follow a similar pattern and thus are related. Figure 20 shows the same comparisons for townhouse #7. Comparing Figure 19 with Figure 20, it is obvious that the average daily energy consumption of the refrigerator in townhouse #8 is higher than that of townhouse #7. The refrigerator door openings also affect the energy usage of the refrigerator, as shown in Table 4.

2.3 ANALYSIS OF THE PARAMETERS THAT AFFECT REFRIGERATOR ENERGY CONSUMPTION

An attempt was made to obtain the effect of various parameters on energy consumption of the refrigerators. For each townhouse, major emphasis was placed on two parameters: (a) the temperature difference between the kitchen and the refrigerator, and (b) the number and duration of its door openings.

Figure 21 shows the daily energy consumption, E, versus temperature difference between kitchen and main section, ΔT_M, of the refrigerator in townhouse #8. The mean value of E is also given as 6.45 kWh with standard deviation equaled to 0.55 kWh, as shown in Table 4. By using the least-squares linear regression technique, the one-parameter model of these variables is given by

$$E = \alpha_0 + \alpha_1 (\Delta T_M), \qquad (1)$$

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where E is the daily energy consumption in kWh, and ΔT_M is the temperature difference between kitchen and main section of the refrigerator in degrees F. The straight line is presented on the same graph and the coefficient of equation 1 was calculated to be $\alpha_0 = 1.56$ and $\alpha_1 = 0.11$.

In equation 1, α_1 could be interpreted as the energy consumed per degree F of temperature difference. Non-zero α_0 of equation 1 indicated that the linear relationship is applicable over a limited range and also that other independent variables should be considered for analysis. The correlation coefficient, R^2, and the standard deviation of the linear regression, σ_ϵ, were obtained as 0.69 and 0.28, respectively. The percentage gained in precision for linear regression, by reducing the standard deviation from 0.55 to 0.28, is 50 percent.

However, R^2 of 0.69 means a better model could be adopted by the method of multiple regression to include more independent variables. Table 5 gives the coefficients α_0 and α_1 of equation 1 together with the correlation coefficient R^2 and standard deviation σ_ϵ for the following variables taken as independently as listed below as determined by the measurements on the refrigerator in each townhouse:

   ° ΔT_M, temperature difference between kitchen and main section

   ° ΔT_F, temperature difference between kitchen and freezer section

   ° ND_M, number of door openings of main section

   ° ND_F, number of door opening of freezer section

   ° tD_M, duration of door openings of main section

   ° tD_F, duration of door openings of freezer section.

From the statistical point of view, the correlation coefficient R^2 is a measure of linear dependence of a dependent variable to the independent variables from the linear equation. Whenever R^2 is extremely small, they are linearly uncorrelated. The results from the linear regression analysis for each of the ten refrigerators are displayed in Table 5. The refrigerators in townhouses #4 and #9 have low R^2 for energy consumed, E, vs differential temperatures, ΔT_M or ΔT_F. As shown in Figures 22 and 23, the data points of E vs ΔT_M or ΔT_F for both townhouses show random scatter. Therefore, low R^2 might be due to data being recorded incorrectly or the physical malfunctioning of the refrigerators. The fitted straight lines are almost horizontal and even show a negative slope of E vs ΔT_M; i.e., α_1 is negative. Another reason for the observed behavior of the data for the refrigerator in townhouse #4 is that only approximately thirty days of data are available, excluding partial days. There might be insufficient data to determine the results accurately. Therefore, the refrigerators in townhouses #4 and #9 could not be represented correctly by the mathematical model of equation 1.

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As for refrigerators in townhouses #1 and #2, the low values or R^2 from E vs ΔT_M again were due to random scatter of data and also the small variations of ΔT_M, approximately 5°F, for refrigerator in townhouse #1, as given in Figure 24. The larger values of R^2 from E vs ΔT_F indicates for these townhouses the energy consumption is better correlated with the differential freezer temperatures, as illustrated in Figure 25. In townhouse #2, there is a highly correlated relationship between energy consumption, E, and the number of main-section door openings, ND_M, of refrigerator.

Furthermore, Figures 24 and 25 also indicated that these two refrigerators were operated at the same range of ΔT_F, while ΔT_M of the refrigerator in townhouse #1 is much higher than that in townhouse #2. Hence, the average daily energy consumed by the refrigerator in townhouse #1 is slightly higher than that in townhouse #2.

In general, the correlation coefficient R^2 had much higher values in temperature differences, ΔT_M and ΔT_F, than those in door openings, with the exceptions discussed previously. That implies that from the linear model of equation 1, the differential temperature between kitchen and refrigerator (either main section or freezer section) affects energy usage more than door openings. The second independent variable chosen for multiple regression analysis may be either the daily number of door openings or the length of door-opening times, since they are somewhat related, as indicated in their hourly profiles (see Figures 3, 5, 6, 7, and 8). For example, an attempt to fit the refrigerator energy usage, E, in townhouse #8 as a function of temperature differences between the kitchen and main section, ΔT_M, and number of main-section door openings, ND_M is as follows. The multiple regression relationship is given by

$$E = \beta_0 + \beta_1 (\Delta T_M) + \beta_2 (ND_M) \qquad (2)$$

where E is the daily energy consumption in kWh, ΔT_M is the temperature difference between kitchen and main section of refrigerator in degree F, and ND_M is the daily number of main-section door openings. The coefficients of equation 2 were found to be $\beta_0 = 1.29$, $\beta_1 = 0.11$ and $\beta_2 = 0.007$, where β_2 is the coefficient denoting energy used in kWh per each door opening. From coefficients of equations 1 and 2, note that $\beta_1 = \alpha_1$, which implies the effect of differential temperature is fairly steady. The correlation coefficients R^2 of equation 2 increased to 0.822 and the standard deviation was reduced to $\sigma_\epsilon = 0.22$. This means equation 2 is a better model than equation 1. The precision gained in standard error with equation 2 is 60 percent, a 10 percent improvement from that with equation 1. Figure 28 is a sketch of predicted energy usage from equation 2 and the data points from measurements.

Table 6 gives the regression coefficients and standard deviation for refrigerators in each townhouse. With some exceptions, the majority values of R^2 have been increased by using a two-parameter model, as can be seen by comparing Table 6 and Table 5. Therefore, it can be concluded that equation 2 is a better mathematical model than equation 1 for predicting daily performance of the standard refrigerators.

3. DISCUSSION OF RESULTS

In order to evaluate the performance of different refrigerator models, a comparison of energy consumption of each refrigerator under the same conditions from its regression coefficients is a proper approach. The overall average values of variables for all ten refrigerators is given in Table 7. The normalized energy consumption of each refrigerator was calculated from its regression coefficients β_0, β_1 and β_2, Table 6, and overall average values, Table 7. Four combinations of variables were considered in each case, as shown in the following expressions:

$$E_{MN} = \beta_0 + \beta_1(\overline{\Delta T_M}) + \beta_2(\overline{ND}_M)$$

$$E_{FN} = \beta_0 + \beta_1(\overline{\Delta T_F}) + \beta_2(\overline{ND}_F)$$

$$E_{Mt} = \beta_0 + \beta_1(\overline{\Delta T_M}) + \beta_2(\overline{tD}_M)$$

$$E_{Ft} = \beta_0 + \beta_1(\overline{\Delta T_F}) + \beta_2(\overline{tD}_F)$$

where E_{MN}, E_{FN}, E_{Mt} and E_{Ft} are normalized energy consumptions calculated from various combinations of overall average values, given in Table 7, with their regression coefficients.

These results are presented in groups according to their type of model, in Table 8, together with the actual measurements of energy consumption and differential temperature between kitchen and refrigerators. Except for the refrigerator in townhouse #7, the four values of energy consumption (E_{MN}, E_{FN}, E_{Mt} and E_{Ft}) of each refrigerator are within the range of ± 5 percent and these values could be considered as the energy usage of each refrigerator under usage conditions.

The refrigerator in townhouse #7 was operated at a fairly high freezer temperature of 14°F, as compared to the overall average freezer temperature of 4.8°F. The average differential temperature between its kitchen and freezer was 65.6°F, as compared to the overall average value of 73.6°F. However, its average main-section temperature was measured to be at 35°F, which is close to the overall value of 36.4°F. By using the normalized freezer temperature difference, $\Delta T_F = 42$°F, to calculate the energy consumptions, E_{FN} and E_{Ft}, the freezer temperature would need to be decreased or ΔT_F would have to be increased by 18°F or about

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12 percent. Hence, the values of E_{FN} and E_{Ft} will be much higher than E_{MN} and E_{Mt}, since ΔT_M was decreased only about 2.7°F or 6 percent. For comparison purposes, E_{FN} and E_{Ft} are more realistic values to use under the normalized condition for the refrigerator in townhouse #7.

It should also be pointed out that, according to the field measurements, it is possible to reduce energy consumption by maintaining a higher freezer temperature. Usually running freezer temperature of a refrigerator at an average value of 14°F would not be recommended by food scientists [5] or for laboratory tests. When operating the refrigerator in townhouse #7 at this freezer temperature, energy consumption was reduced by 18 percent as compared to the normal condition.

Table 8 and Figure 29 also show that the energy consumption of refrigerators increases with their physical size, as expected. However, the energy consumption of the refrigerator in townhouse #4, as compared to other 14.7 ft^3 models, do not fit the attempted correlation.

For the purpose of simplification, an average value $\overline{E}$ for these four cases was considered to be the normalized energy consumption per day for the refrigerator in each townhouse. These values are also included at the last column in Table 8. The relationship between the daily normalized energy consumption and physical size of refrigerators also can be seen to be linear. Again, regression analysis was utilized to fit a straight line for these data. Figure 29 shows the data points as well as the regression line for refrigerators in all townhouses except the one in townhouse #3. This refrigerator was a manual-defrost model and the rest were frost-free models.

Table 9 gives the parameters from the regression analysis. From Figure 29, the predicted value of $\overline{E}$ was found to be 3.54 kWh for $V = 11.5$ ft^3. Comparing it to $E_3 = 2.14$ kWh, the energy savings between a manual-defrost model and the frost-free model with this size is 1.4 kWh, or about 40 percent per day. As for other size models, there was no valid information available to make estimations. However, the results of the laboratory test of refrigerators by Mulroy et al. [6] were found to be quite interesting when compared with Figure 29. Under 75°F kitchen temperature with door-opening conditions, the daily energy consumption for a 14.7 ft^3 frost-free refrigerator was found to be 5.12 kWh.* The predicted value in Figure 29 is 5.3 kWh, only a 3.5 percent difference. As for the manual-defrost model, the daily energy usage for the 14.7 ft^3 refrigerator was found to be 2.91 kWh*, which is 38 percent below the expected value, 4.7 kWh, for the frost-free model in the same size. Consequently, the regression line in Figure 29 indicates the differences in energy consumption per day for various sizes of frost-free refrigerators under the normal usage pattern. The energy usage was found to be 0.55 kWh for each additional cubic foot of volume for the frost-free model. The approximate

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* Average value for the two relative humidity settings.

percentage of saving in energy consumption of refrigerators from a frost-free model to a manual-defrost model could also be estimated from Figure 29 and the above calculations.

4. CONCLUSION

The hourly profiles of the refrigerator showed that occupants opened the doors much more at lunch time and dinner time. The door openings usually dropped to zero from midnight to 6:00 am. The hourly energy consumption was consistent with this pattern (heaviest at lunch and dinner times) except at the time immediately following the refrigerator self-defrost cycle, when additional energy was used to reduce the temperature inside the refrigerator.

By analyzing the daily performance of residential refrigerators, it was concluded that the differential temperature between the kitchen and the refrigerator dominated its energy usage, with lesser, though still important, effects from door openings.

The daily energy consumption is linearly related to the physical sizes of refrigerators. It was estimated that there would be about 0.55 kWh increase per day for each cubic foot increase in volume for the frost-free refrigerators. The energy conserved by using a manual defrost refrigerator was found to be approximately 40 percent of that for the frost free model.

5.   TABLES AND FIGURES

TABLE 1

REFRIGERATOR PHYSICAL CHARACTERISTICS

Townhouse Number	Model*	Ft^3	Frost Free	No. of Doors
1	TBF-15S	14.7	yes	2
2	TBF-15S	14.7	yes	2
3	TA-12S	11.5	no	1
4	TBF-15S	14.7	yes	2
5	TBF-15S	14.7	yes	2
6	18-CMB	18.0	yes	2
7	TBF-16S	15.6	yes	2
8	TBF-16S	15.6	yes	2
9	TFF-15J	14.7	yes	2
10	TBF-19D	19.0	yes	2-S

* All refrigerator models were from the same manufacturer, as
supplied by the developer or purchased by the occupants.

TABLE 2

OCCUPANT AND TOWNHOUSE CHARACTERISTICS

Townhouse Number	Number of Adults	Number of Children	Children's Ages	Number of Bedrooms
1	2	2	6,8	3
2	2	1	6	3
3	2	1	3	2
4	2	3	6,7,9	3
5	2	2	10,13	3
6	2	2	10,13	4
7	2	2	2,4	3
8	2	2	1,3	3
9	3	1	15	3
10	2	2	2,6	2 converted to 3

TABLE 3 SUMMARY OF AVERAGE HOURLY ENERGY AND DOOR OPENINGS
OF THE REFRIGERATOR IN EACH TOWNHOUSE

ENERGY CONSUMED (KWH) BY HOURS

TOWN HOUSE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.19	0.19	0.18	0.17	0.18	0.20	0.21	0.19	0.20	0.20	0.18	0.21	0.21	0.20	0.23	0.23	0.23	0.24	0.25	0.25	0.25	0.23	0.21	0.19
2	0.18	0.16	0.16	0.14	0.16	0.14	0.15	0.17	0.20	0.20	0.18	0.21	0.22	0.20	0.20	0.20	0.23	0.24	0.24	0.23	0.22	0.22	0.20	0.18
3	0.07	0.07	0.07	0.07	0.07	0.06	0.08	0.06	0.08	0.08	0.08	0.09	0.08	0.08	0.08	0.09	0.09	0.10	0.09	0.09	0.09	0.08	0.08	0.08
4	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.29	0.30	0.29	0.29	0.29	0.29	0.30	0.30	0.30	0.30	0.30	0.29	0.29
5	0.21	0.19	0.18	0.19	0.18	0.19	0.17	0.20	0.20	0.21	0.21	0.20	0.21	0.20	0.22	0.21	0.22	0.24	0.23	0.21	0.21	0.23	0.22	0.20
6	0.29	0.25	0.25	0.29	0.23	0.24	0.25	0.29	0.27	0.29	0.31	0.29	0.32	0.30	0.29	0.28	0.33	0.35	0.36	0.34	0.33	0.30	0.30	0.30
7	0.19	0.21	0.20	0.19	0.19	0.20	0.19	0.20	0.24	0.24	0.24	0.26	0.26	0.26	0.26	0.25	0.27	0.29	0.28	0.26	0.24	0.23	0.22	0.22
8	0.25	0.25	0.24	0.24	0.24	0.23	0.25	0.27	0.28	0.28	0.28	0.29	0.28	0.27	0.27	0.28	0.29	0.29	0.30	0.30	0.30	0.27	0.27	0.26
9	0.18	0.18	0.18	0.17	0.18	0.17	0.17	0.21	0.21	0.19	0.21	0.23	0.21	0.21	0.22	0.22	0.23	0.25	0.23	0.23	0.22	0.20	0.20	0.19
10	0.35	0.35	0.35	0.33	0.32	0.32	0.32	0.32	0.32	0.35	0.34	0.35	0.35	0.34	0.35	0.35	0.35	0.36	0.37	0.36	0.36	0.36	0.35	0.34

NUMBER OF MAIN SECTION DOOR OPENINGS BY HOURS

TOWN HOUSE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0.12	0	0.04	0	0.06	2.64	4.12	1.67	2.14	1.55	1.41	2.51	1.42	1.59	2.62	2.17	3.74	4.70	4.12	3.17	1.66	1.10	0.51	0.19
2	0.19	0.09	0.16	0	0	0.17	1.17	2.95	4.67	3.14	2.59	4.62	4.06	2.10	2.07	2.37	4.90	5.88	3.90	2.94	2.49	1.67	0.88	0.33
3	0.17	0	0	0.07	0	0.40	1.57	2.45	2.97	2.41	2.32	2.45	2.07	2.00	1.82	2.43	3.87	7.50	3.91	2.74	3.56	1.95	1.26	0.74
4	0.05	0	0	0	0.02	0.88	0.40	2.92	2.45	2.10	3.77	3.84	1.77	1.25	3.18	2.20	3.71	5.22	3.38	2.28	1.40	1.19	0.67	0.21
5	0.16	0.11	0.11	0.03	?	0.01	0.74	1.79	2.12	1.89	1.37	1.79	1.15	0.97	1.47	1.04	2.41	3.15	1.63	1.07	1.78	2.02	0.61	0.36
6	0.42	0.09	0.29	0.13	0.17	0.06	1.33	2.14	2.44	3.17	3.13	4.00	2.98	1.64	1.53	1.95	3.42	6.25	3.59	2.30	2.33	1.86	2.05	0.95
7	0.11	0.02	0	0	0.05	1.08	0.14	1.54	7.40	4.93	3.99	5.73	4.96	2.28	3.49	3.75	5.43	8.23	4.86	1.70	1.57	0.65	0.25	0.21
8	0.18	0.02	0	0	0	0.25	1.90	5.80	5.27	4.05	4.78	4.20	4.10	2.19	2.85	3.39	4.42	6.00	5.72	4.81	3.06	1.02	0.75	0.56
9	0.05	0.20	0.01	0.05	0.03	0.76	1.16	5.62	4.29	3.25	2.76	4.19	2.94	2.48	2.86	2.83	5.05	5.55	2.68	1.42	2.34	2.08	0.72	0.50
10	0.16	0.01	0	0	0.03	0.64	0.04	0.25	2.84	5.23	2.30	2.90	3.16	1.73	1.61	1.03	1.21	5.09	4.16	3.20	2.17	1.34	1.05	0.30

NUMBER OF FREEZER DOOR OPENINGS BY HOURS

TOWN HOUSE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15*	16	17	18	19	20	21	22	23	24
1	0.03	0	0.01	0	0	0.05	0.12	0.07	0.11	0.09	0.49	0.73	0.44	0.71	1.71	1.15	1.34	1.25	0.91	1.76	0.90	0.77	0.11	0.11
2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
4	0	0	0	0	0	0	0	0.48	0.15	0.41	0.34	0.36	0.30	0.41	0.48	0.43	0.67	1.85	0.71	0.12	0.19	0.21	0.19	0
5	0.04	0.01	0.02	0.02	0	0	0.01	0.21	0.26	0.31	0.15	0.47	0.44	0.39	0.35	0.41	1.02	1.15	0.45	0.42	0.75	0.50	0.22	0.13
6	0.05	0.03	0.06	0.03	0.03	0	0.11	0.21	0.24	0.48	0.52	1.05	0.47	0.18	0.42	0.23	0.80	1.58	0.77	0.34	0.53	0.55	0.38	0.14
7	0	0	0	0	0	0	0	0.02	0.27	0.24	0.59	0.48	0.83	0.25	0.57	0.61	0.94	1.99	0.82	0.20	0.40	0.20	0.04	0
8	0	0	0	0	0	0.02	0.25	0.39	0.57	0.40	0.40	0.77	0.54	0.31	0.51	0.80	2.04	1.71	1.55	1.21	0.81	0.19	0.08	0.06
9	0.01	0.01	0	0	0	0.22	0.30	0.58	0.42	0.65	0.45	0.58	0.53	0.53	0.68	0.92	1.24	1.51	0.76	0.55	0.75	0.55	0.20	0.09
10	0.05	0	0	0	0.01	0.18	0	0.01	0.28	0.49	0.16	0.31	0.56	0.30	0.28	0.16	0.59	1.30	0.33	0.83	0.88	0.64	0.38	0.08

*   Missing Data
** No Measurements

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TABLE 4   DAILY REFRIGERATOR PERFORMANCE

# Townhouse Number	E Energy Consump. kWh/Day	T_K Kitchen Temp. Deg. F	T_M Main Sec. Temp. Deg. F	T_F Freezer Temp. Deg. F	ND_M No. of Main Sec. Door Openings	tD_M Time of Main Sec. Door Open. Sec.	ND_F No. of Freezer Door Openings	tD_F Time of Freezer Door Open. Sec.	Days of Measurem.
1	5.03 (0.52)	77.8 (0.7)	33.8 (1.2)	3.1 (3.7)	42.8 (25.3)	444.5 (217.2)	12.5 (8.9)	131.5 (110.8)	166-249
2	4.64 (0.51)	76.3 (1.0)	43.1 (2.0)	3.8 (1.1)	53.2 (19.6)	1117.5 (1304.1)	*	*	166-249
3	2.30 (0.27)	85.8 (3.2)	39.2 (1.8)	**	47.7 (19.5)	632.8 (311.6)	**	**	216-280
4	6.87 (0.51)	77.3 (2.0)	38.4 (5.2)	4.3 (3.0)	44.9 (35.2)	698.3 (668.0)	7.8 (8.0)	100.6 (146.2)	216-280
5	4.93 (0.71)	78.2 (1.9)	35.0 (1.2)	*	27.2 (11.6)	1783.0 (1020.6)	9.6 (4.0)	347.8 (257.0)	176-280
6	7.04 (0.67)	78.7 (1.3)	38.5 (1.0)		47.2 (18.3)	2654.0 (1069.4)	9.1 (4.8)	460.2 (664.7)	176-280
7	5.56 (0.92)	79.7 (3.4)	35.0 (0.8)	14.1 (2.3)	62.0 (27.4)	571.4 (176.0)	8.4 (4.6)	63.4 (37.8)	96-180
8	6.45 (0.55)	77.6 (3.5)	33.4 (0.9)	5.5 (0.9)	64.9 (26.3)	711.9 (647.9)	12.5 (6.8)	157.7 (218.4)	96-180
9	4.91 (0.57)	73.3 (1.9)	34.3 (0.5)	2.0 (2.7)	53.9 (10.3)	636.4 (203.9)	11.6 (4.4)	154.8 (104.3)	92-174
10	8.22 (0.45)	79.2 (2.2)	32.9 (1.0)	0.7 (1.8)	40.2 (24.8)	941.6 (1189.1)	7.5 (5.9)	177.6 (315.4)	92-174

Numbers in Parentheses Indicate Standard Deviation

* Missing Data

** No Measurements

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TABLE 5 COEFFICIENTS OF LINEAR REGRESSION PERFORMANCE EQUATION

$$E = \alpha_0 + \alpha_1 X$$

Town House #	$X = \Delta T_M$				$X = ND_M$				$X = tD_M$			
	α_0	α_1	σ_ϵ	R^2	α_0	α_1	σ_ϵ	R^2	α_0	α_1	σ_ϵ	R^2
1	0.151	0.110	0.468	0.082	4.712	0.007	0.484	0.129	4.694	0.0008	0.520	0.103
2	5.703	-0.032	0.482	0.030	3.528	0.021	0.293	0.663	4.457	0.0002	0.449	0.157
3	0.003	0.049	0.217	0.375	2.002	0.006	0.240	0.232	2.077	0.0004	0.247	0.185
4	7.879	-0.020	0.375	0.093	6.785	0.002	0.513	0.018	6.587	0.0004	0.305	0.376
5	-2.320	0.167	0.409	0.514	4.217	0.024	0.469	0.262	4.076	0.0005	0.509	0.472
6	-3.521	0.262	0.521	0.401	5.977	0.022	0.529	0.379	6.127	0.0003	0.562	0.300
7	-3.464	0.202	0.451	0.761	4.613	0.015	0.821	0.207	4.652	0.002	0.868	0.110
8	1.798	0.106	0.281	0.692	6.088	0.006	0.481	0.098	6.278	0.0003	0.474	0.135
9	5.552	-0.017	0.575	0.004	3.829	0.020	0.537	0.130	3.963	0.001	0.470	0.288
10	1.752	0.139	0.291	0.583	8.134	0.002	0.452	0.015	8.192	0.0003	0.454	0.008

Town House #	$X = \Delta T_F$				$X = ND_F$				$X = tD_F$			
	α_0	α_1	σ_ϵ	R^2	α_0	α_1	σ_ϵ	R^2	α_0	α_1	σ_ϵ	R^2
1	-2.298	0.098	0.316	0.577	4.865	0.013	0.506	0.050	4.905	0.0004	0.509	0.040
2	-9.964	0.201	0.386	0.437	*	*	*	*	*	*	*	*
3	0.778	0.023	0.246	0.193	**	**	**	**	**	**	**	**
4	2.518	0.060	0.339	0.260	6.762	0.021	0.356	0.186	6.794	0.001	0.342	0.247
5	*	*	*	*	4.376	0.064	0.480	0.226	4.671	0.0006	0.565	0.071
6	*	*	*	*	6.606	0.047	0.632	0.115	6.929	0.0002	0.654	0.053
7	-4.563	0.154	0.398	0.812	5.021	0.063	0.873	0.104	5.236	0.005	0.902	0.043
8	-1.355	0.109	0.282	0.689	6.171	0.024	0.478	0.109	6.537	0.0005	0.541	0.046
9	4.754	0.002	0.576	0.0002	4.675	0.020	0.569	0.025	4.675	0.002	0.554	0.075
10	-2.369	0.135	0.231	0.737	8.097	0.017	0.444	0.049	8.258	0.0001	0.447	0.009

* Missing Data

** No Measurements

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TABLE 6   COEFFICIENTS OF MULTIPLE REGRESSION PERFORMANCE EQUATION

$$E = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

$X_1 = \Delta T_M, \; X_2 = ND_M$

House #	β_0	β_1	β_2	σ_ϵ	R^2
1	-1.33	0.135	0.009	0.458	0.232
2	3.513	0.0004	0.021	0.295	0.663
3	-0.562	0.054	0.007	0.158	0.678
4	7.897	-0.026	0.0009	0.380	0.100
5	-2.253	0.153	0.019	0.345	0.657
6	-2.636	0.218	0.019	0.364	0.705
7	-3.270	0.186	0.008	0.408	0.807
8	1.290	0.107	0.007	0.215	0.822
9	4.081	-0.006	0.020	0.541	0.131
10	1.901	0.136	-0.0006	0.292	0.567

$X_1 = \Delta T_F, \; X_2 = ND_F$

House #	β_0	β_1	β_2	σ_ϵ	R^2
1	-3.658	0.112	0.022	0.282	0.709
2	*	*	*	*	*
3	**	**	**	**	**
4	0.445	0.085	0.032	0.236	0.651
5	*	*	*	*	*
6	*	*	*	*	*
7	-4.553	0.150	0.030	0.380	0.832
8	-1.432	0.105	0.024	0.232	0.794
9	4.326	0.005	0.021	0.573	0.026
10	-2.226	0.133	-0.0002	0.230	0.737

$X_1 = \Delta T_M, \; X_2 = tD_M$

House #	β_0	β_1	β_2	σ_ϵ	R^2
1	-1.99	0.152	0.0008	0.432	0.228
2	5.426	-0.029	0.0001	0.448	0.174
3	-0.736	0.059	0.0005	0.154	0.695
4	7.767	-0.023	0.0001	0.368	0.153
5	-2.402	0.159	0.0003	0.358	0.630
6	-3.046	0.229	0.0003	0.369	0.691
7	-3.346	0.200	0.0000	0.454	0.761
8	1.744	0.103	0.0003	0.228	0.801
9	4.038	-0.0004	0.001	0.504	0.246
10	1.939	0.136	0.00005	0.292	0.568

$X_1 = \Delta T_F, \; X_2 = tD_F$

House #	β_0	β_1	β_2	σ_ϵ	R^2
1	-3.869	0.116	0.002	0.275	0.722
2	*	*	*	*	*
3	**	**	**	**	**
4	0.495	0.086	0.002	0.212	0.720
5	*	*	*	*	*
6	*	*	*	*	*
7	-4.700	0.153	0.003	0.387	0.827
8	-1.461	0.109	0.0005	0.247	0.712
9	3.636	0.014	0.002	0.555	0.083
10	-2.273	0.133	0.00004	0.225	0.748

*Missing Data
**No Measurements

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TABLE 7

OVERALL VALUES OF THE REFRIGERATORS

	°F	Number	Seconds
Average Kitchen Temperature $\overline{T}_K$	78.4		
Average Main Section Temperature $\overline{T}_M$	36.4		
Average Freezer-Section Temperature $\overline{T}_F$	4.8		
Average Temperature Difference Across Main Section, $\Delta\overline{T}_M$	42.0		
Average Temperature Difference Across Freezer Section, $\Delta\overline{T}_F$	73.5		
Average Number Main-Section Door-openings per Day, $\overline{ND}_M$		48	
Average Time of Main Section Door-openings per day, $\overline{tD}_M$			1019
Average Number of Freezer Section Door-openings per day, $\overline{ND}_F$		10	
Average Time of Freezer Section Door-openings per day, $\overline{tD}_F$			199

TABLE 8   NORMALIZED ENERGY CONSUMPTION OF REGRIGERATORS

# Townhouse Number	V REF Volume Cu.Ft.	$\dot{E}$ Energy Consump. kWh/Day	ΔT_M Diff.Temp. (T_K-T_M) Deg. F	ΔT_F Diff.Temp. (T_K-T_F) Deg. F	E_{MN} Engy.Cons. $\overline{\Delta T_M}$=42°F ND_M=48.4 kWh/Day	E_{FN} Engy.Cons. ΔT_F=42°F ND_F=10 kWh/Day	E_{Mt} Engy.Cons. ΔT_M=42°F tD_M=1019s kWh/Day	E_{Ft} Engy.Cons. ΔT_F=73.6°F tD_F=199s kWh/Day	$\overline{E}$ Avg. Value of $E_{MN},E_{FN},\overline{E}_{Mt}$ & $\overline{E}_{Ft}$ kWh/Day
3	11.5	2.3	46.6	**	2.04	**	2.25	**	2.14
1	14.7	5.03	44.0	74.7	4.77	4.81	5.21	5.06	4.96
2	14.7	4.64	33.2	72.5	4.55	*	4.30	*	4.42
4	14.7	6.87	38.4	73.0	6.85	7.01	6.90	7.22	6.99
5	14.7	4.93	43.2	*	5.09	*	4.58	*	4.83
9	14.7	4.91	39.0	71.3	4.80	4.9	5.04	5.06	4.95
7	15.6	5.56	44.7	65.6	4.93	6.78	5.05	7.15	5.98
8	15.6	6.45	44.2	72.1	6.12	6.53	6.37	6.66	6.42
6	18.0	7.04	40.2	*	7.44	*	6.87	*	7.15
10	19.0	8.22	46.3	78.5	7.58	7.56	7.70	7.51	7.58

* Missing Data
** No Measurements

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TABLE 9   PARAMETERS FOR LEAST-SQUARES FIT OF REFRIGERATOR ENERGY
CONSUMPTION VERSUS THEIR SIZES   (SEE FIGURE 29)

```
LEAST SQUARES NON-LINEAR FIT
   SAMPLE SIZE N =      9
   MODEL-- Y = A0 +A1*X
   REPLICATION CASE
   REPLICATION STANDARD DEVIATION  =        .9123376384+00
   REPLICATION DEGREES OF FREEDOM  =       5
   NUMBER OF DISTINCT SUBSETS      =       4

ITERATION   CONVERGENCE    RESIDUAL   *   PARAMETER
NUMBER       MEASURE       STANDARD   *   ESTIMATES
                           DEVIATION  *
------------------------------------*--------------
  1--        .10000-01     .84675+00  *   -.51670+01      .69902+00
  2--        .50000-02     .80216+00  *   -.28261+01      .55549+00
  3--        .25000-02     .80214+00  *   -.27774+01      .55241+00

FINAL PARAMETER ESTIMATES                  (APPROX. ST. DEV.)
  1 A0                    -2.77718          ( 2.757  )
  2 A1                      .552397         (  .1743 )

   RESIDUAL    STANDARD DEVIATION      =        .8021400273
   RESIDUAL    DEGREES OF FREEDOM      =       7
   REPLICATION STANDARD DEVIATION      =        .9123376384
   REPLICATION DEGREES OF FREEDOM      =       5
   LACK OF FIT F RATIO =      .2056  = THE  17.9257% POINT OF THE
   F DISTRIBUTION WITH      2 AND     5 DEGREES OF FREEDOM
```

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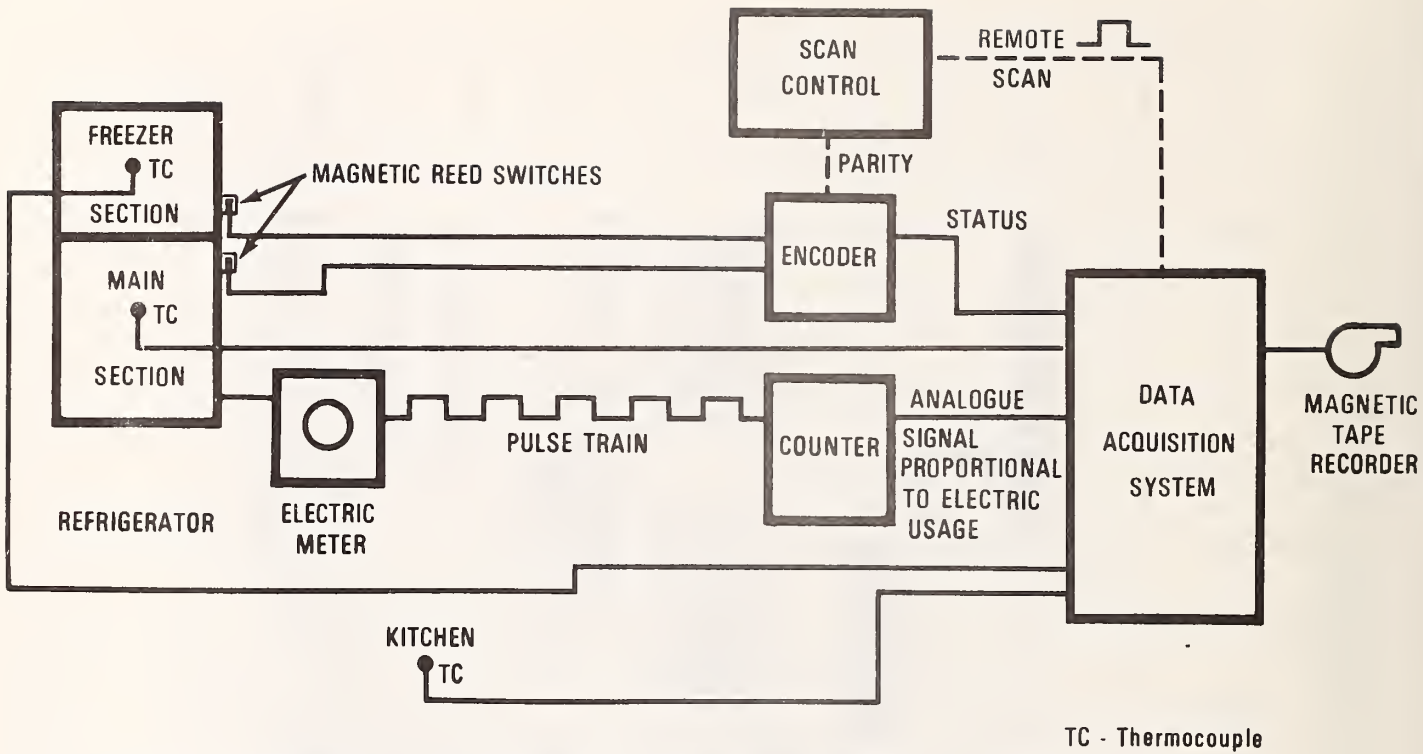
Figure 1   Schematic of Refrigeration Instrumentation
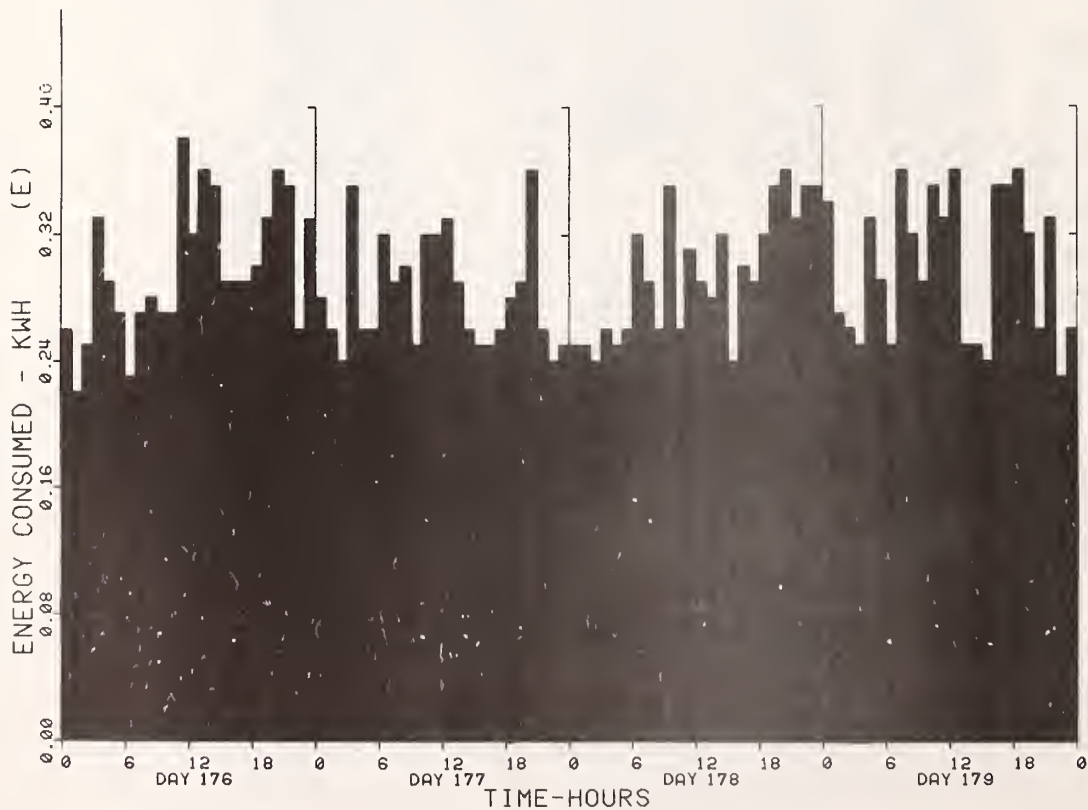
Figure 2   Refrigerator Hourly Energy Consumption (Townhouse 8)
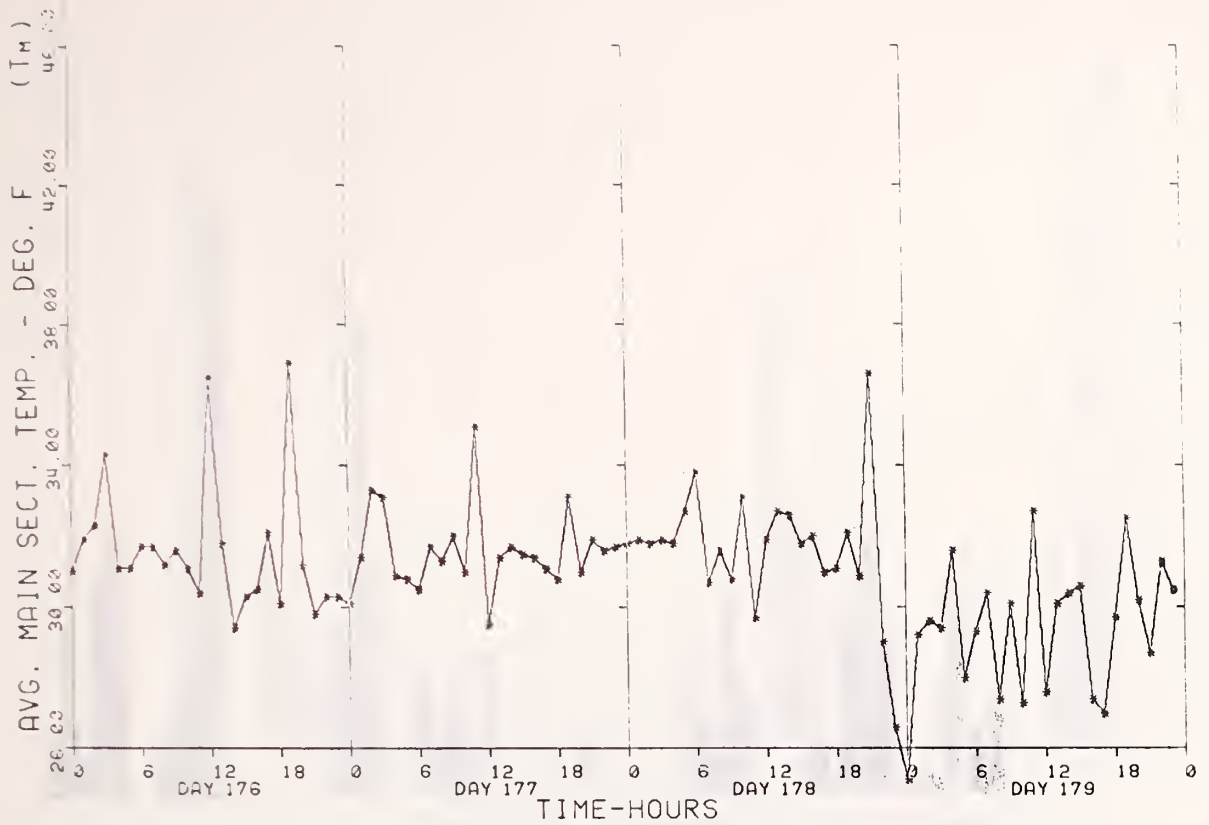
Figure 3 Hourly Main Section Average Temperature (Townhouse 8)
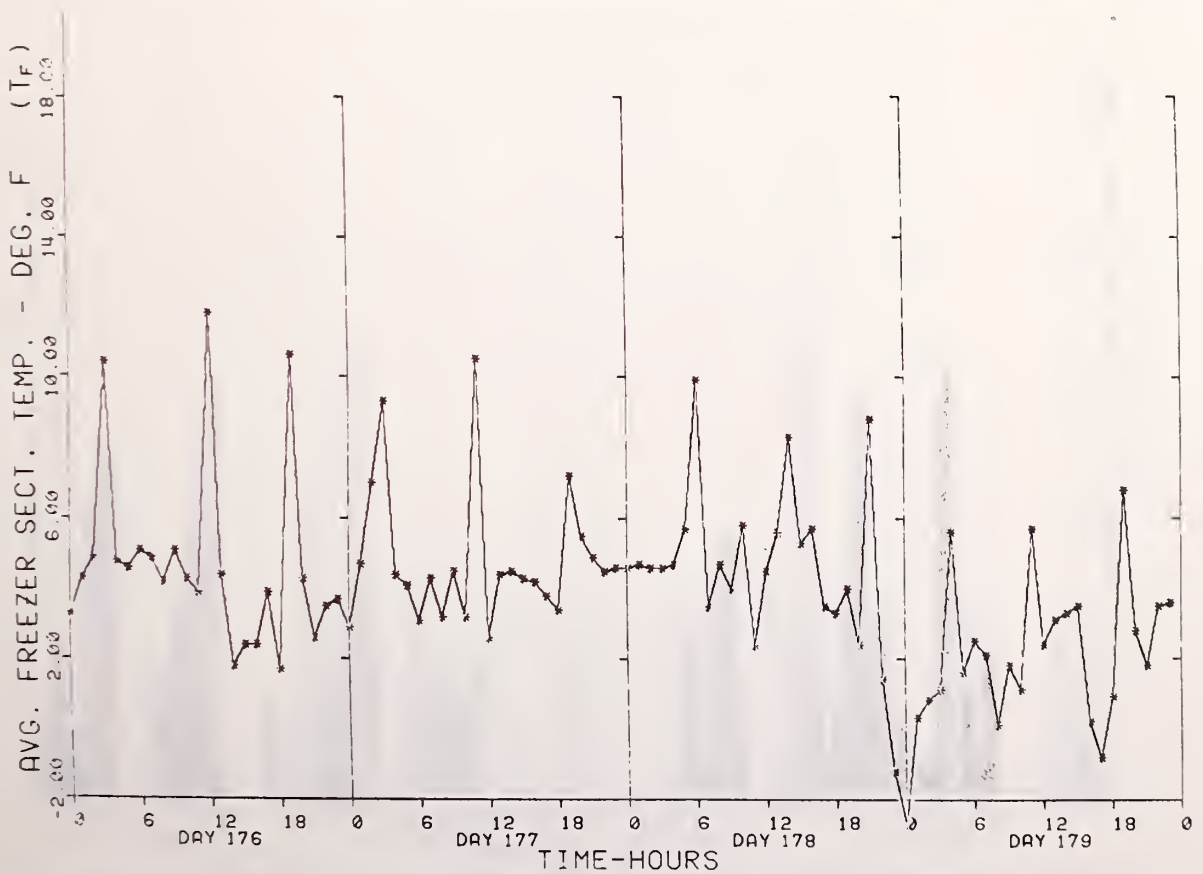
Figure 4 Hourly Freezer Average Temperature (Townhouse 8)

21
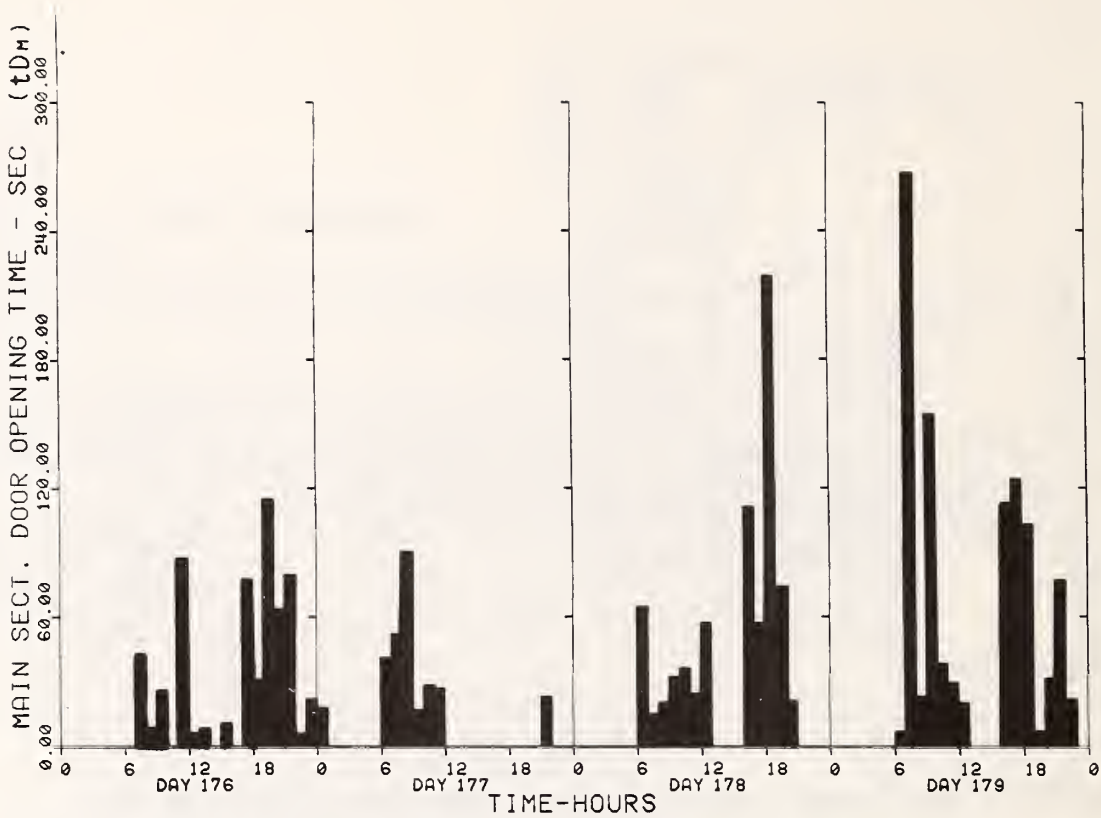
Figure 5   Hourly Main Section Door Opening Time (Townhouse 8)
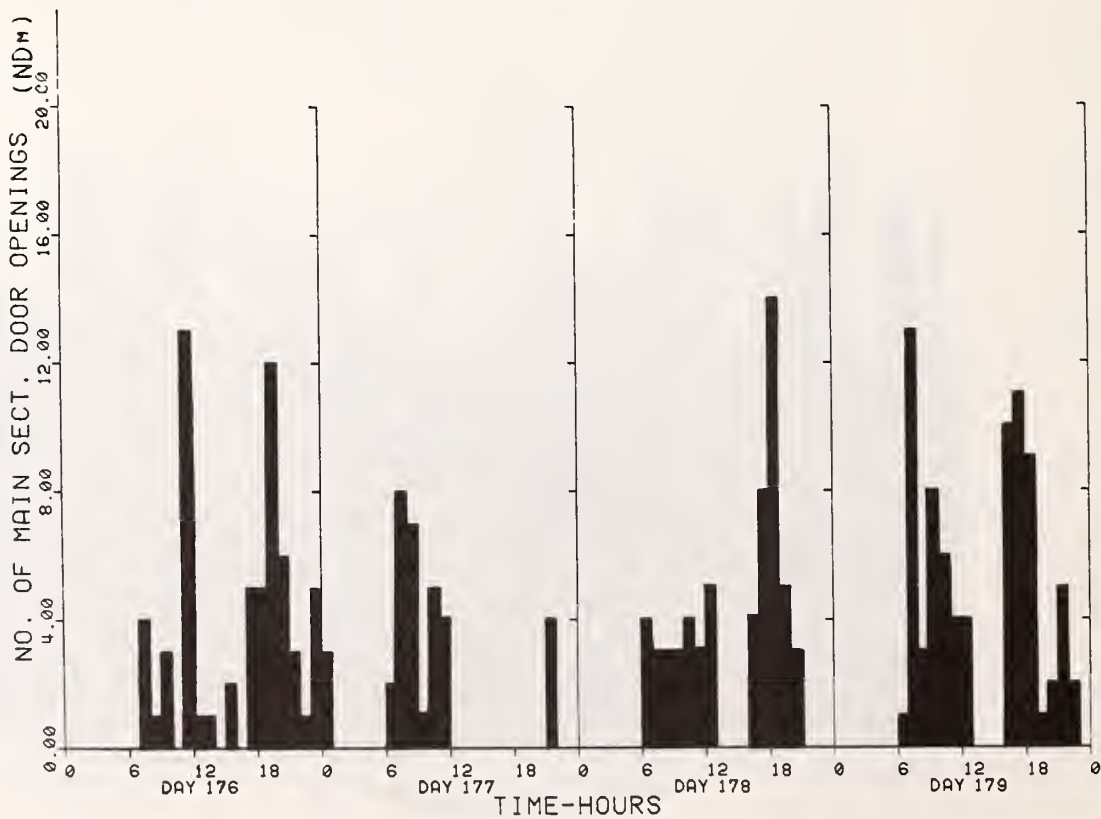
Figure 6   Hourly Number of Main Section Door Openings (Townhouse 8)

22
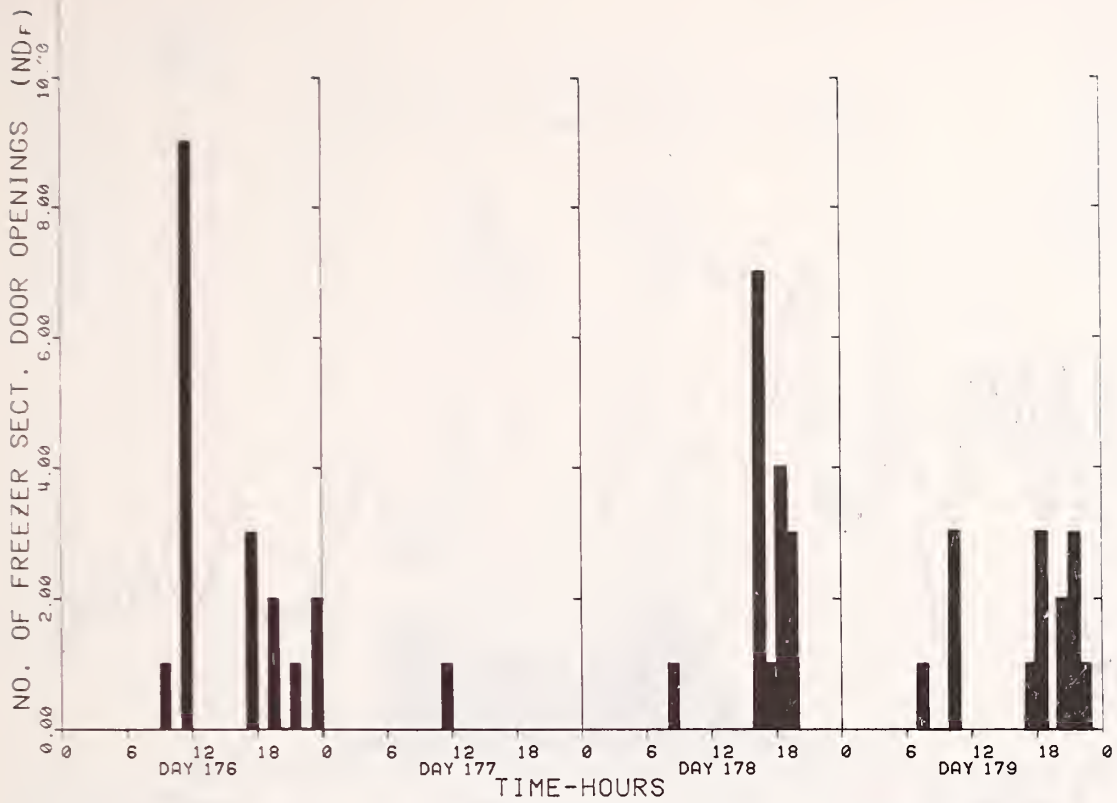
Figure 7   Hourly Number of Freezer Door Openings (Townhouse 8)
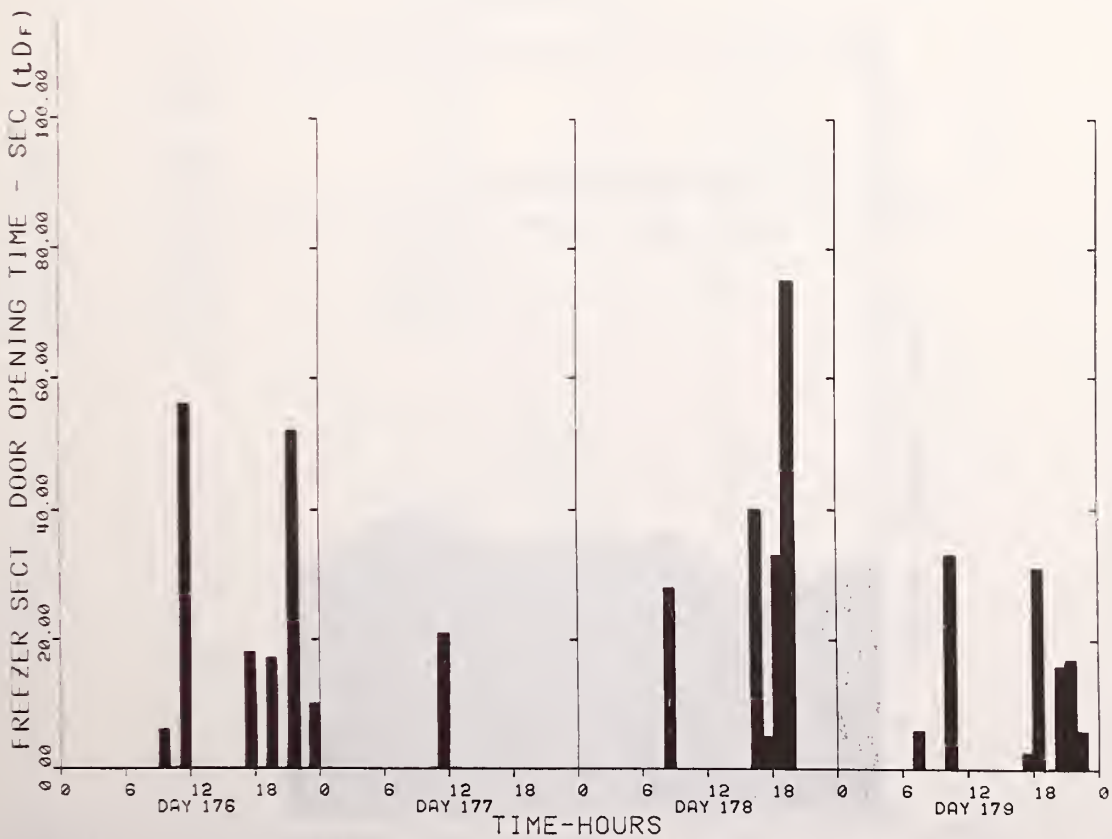
Figure 8   Hourly Freezer Door Opening Time (Townhouse 8)

23
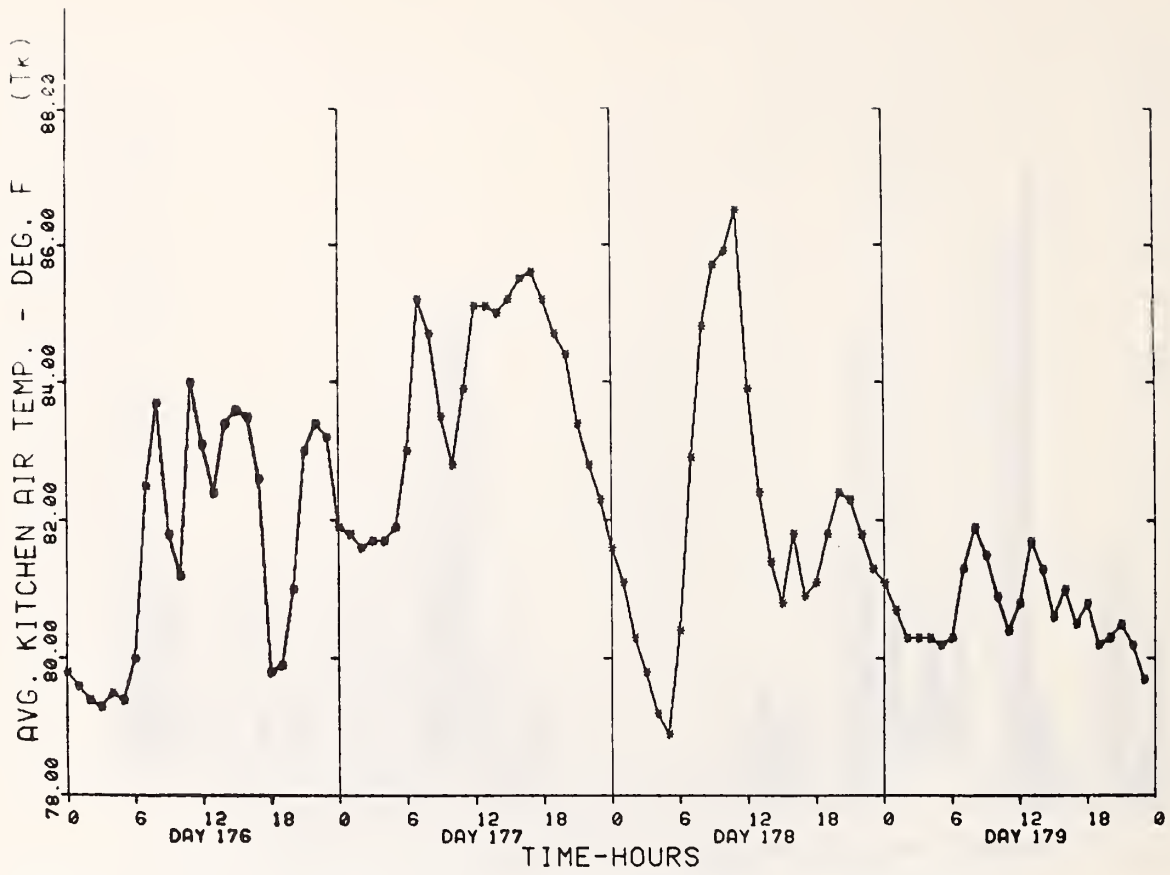
Figure 9 Hourly Average Kitchen Air Temperature (Townhouse 8)
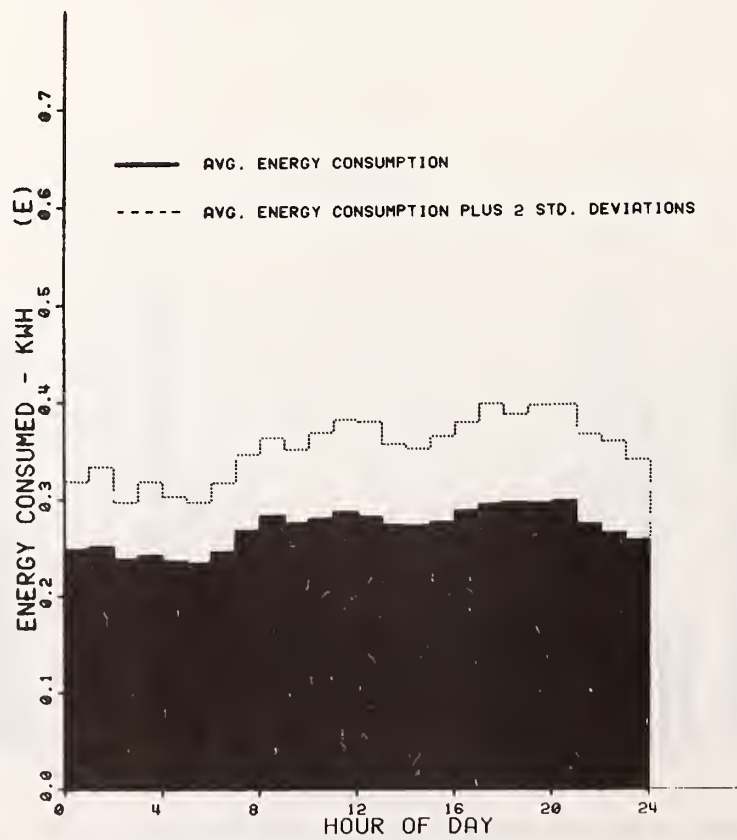
Figure 10 Refrigerator Hourly Profile (Townhouse 8, days 96-180)

24
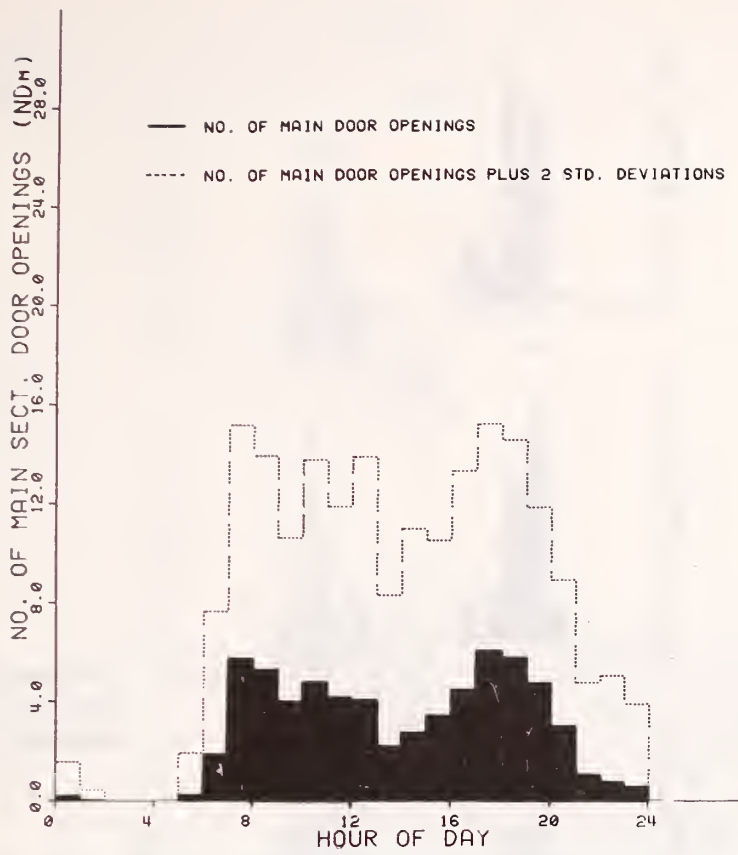
Figure 11 Refrigerator Hourly Profile, Main Section Door Openings
(Townhouse 8, days 96–180)
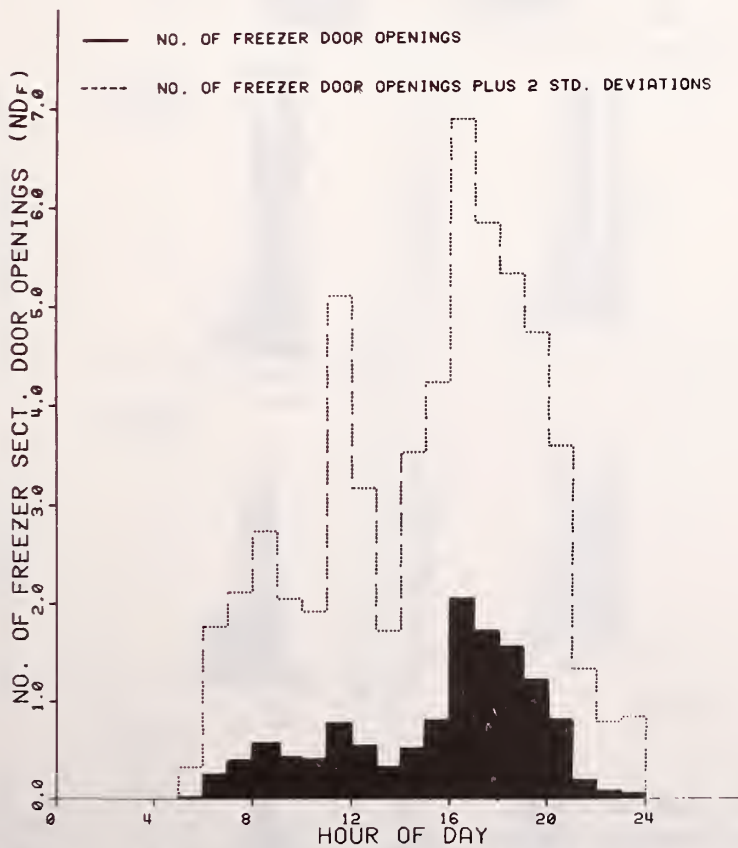
Figure 12 Refrigerator Hourly Profile, Freezer Door Openings
(Townhouse 8, days 96–180)

25
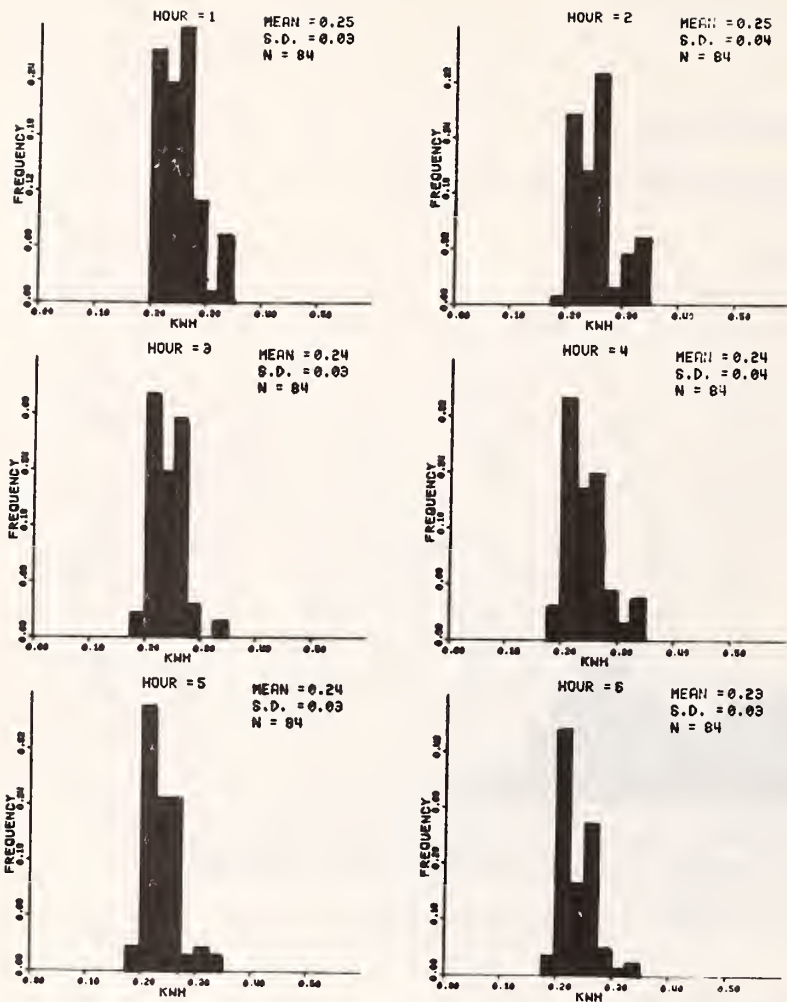
Figure 13   Frequency Distributions, Townhouse 8 Hourly Energy Consumption (hours 1-6)
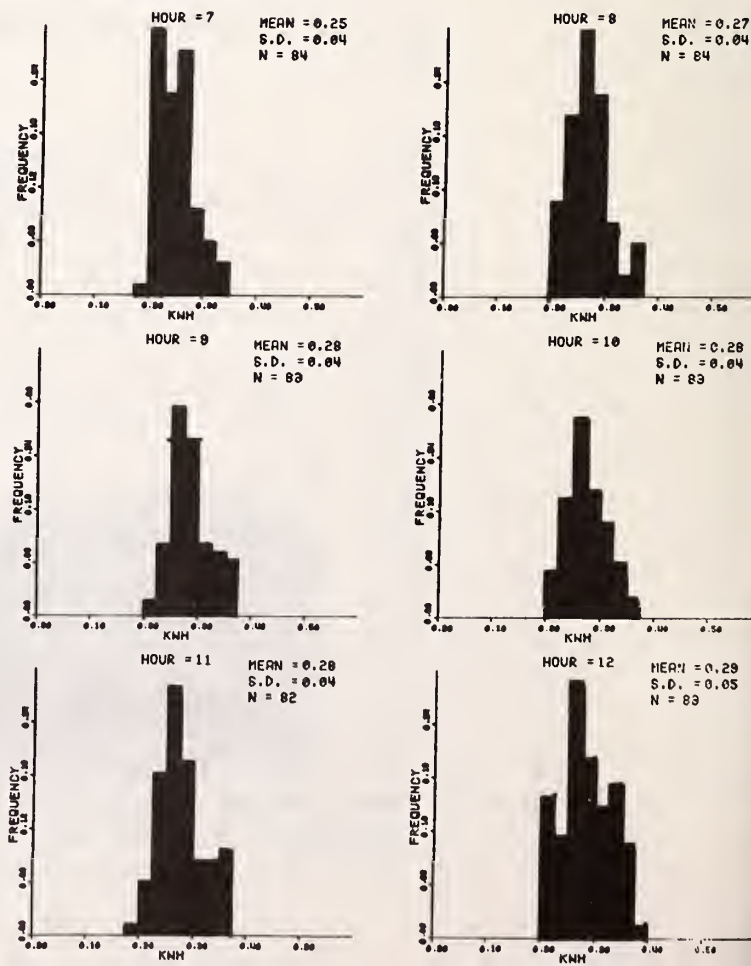
Figure 14   Frequency Distributions, Townhouse 8 Hourly Energy Consumption (hours 7-12)

26
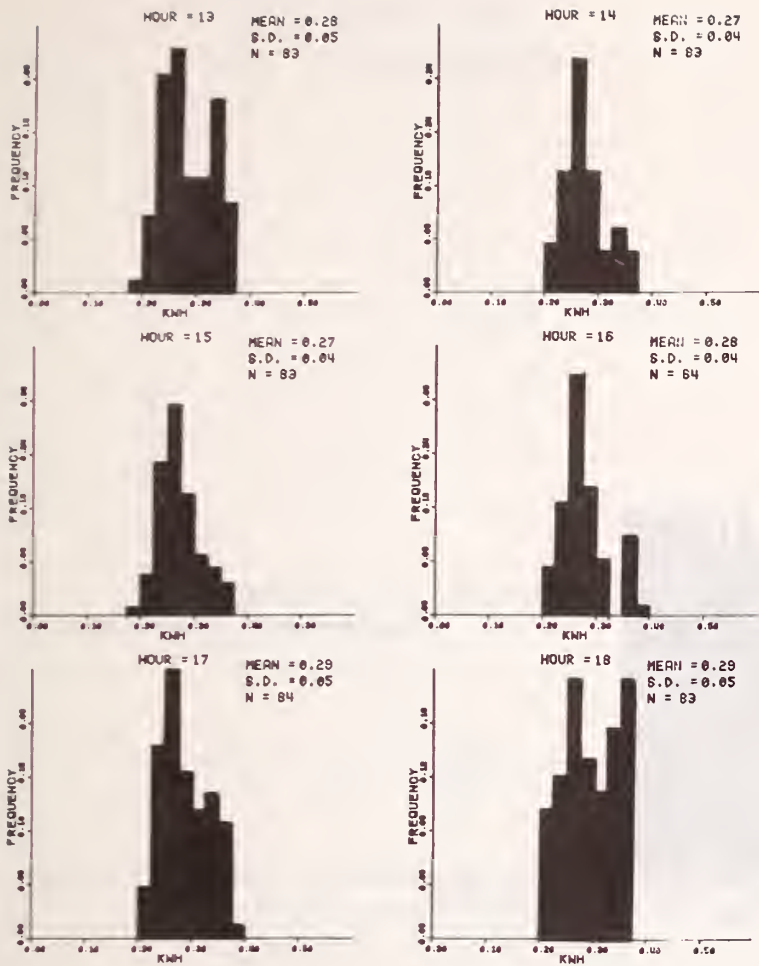
Figure 15   Frequency Distributions,
Townhouse 8 Hourly Energy
Consumption (hours 13-18)
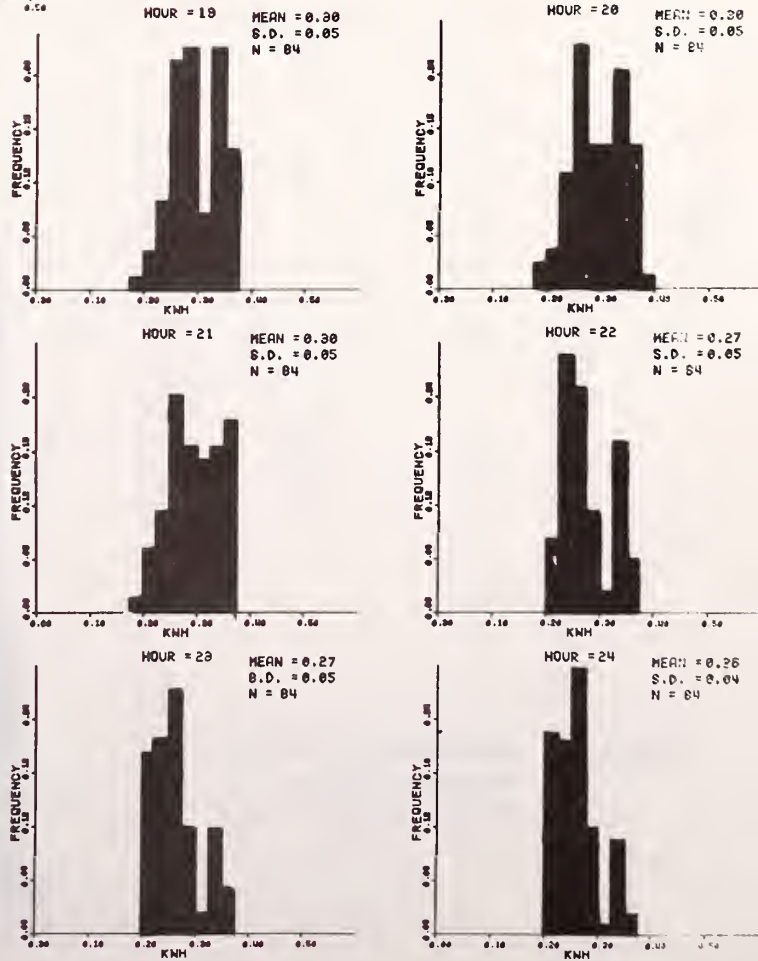
Figure 16   Frequency Distributions,
Townhouse 8 Hourly Energy
Consumption (hours 19-24)

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MEAN = 6.45
S.D. = 0.55
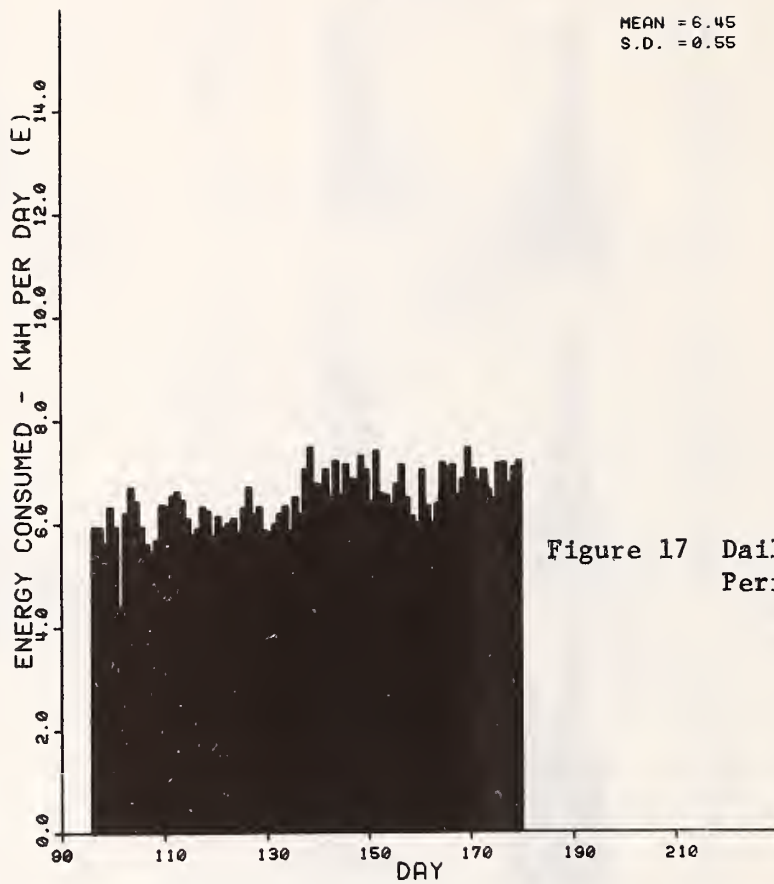
Figure 17   Daily Refrigerator
Performance (Townhouse 8)

MEAN = 6.45
S.D. = 0.55
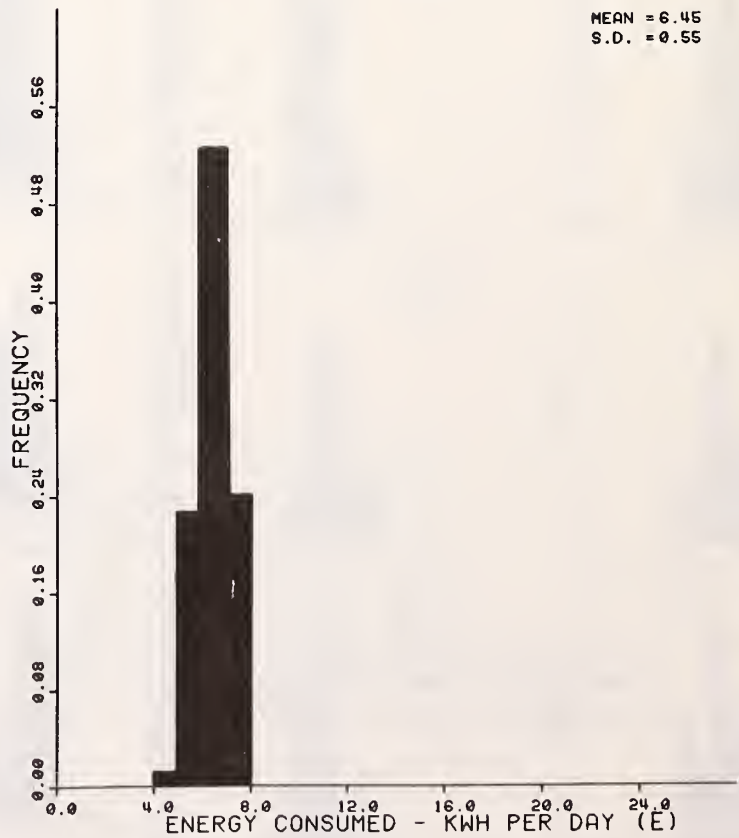
Figure 18   Refrigerator Daily
Frequency Plot
(Townhouse 8)
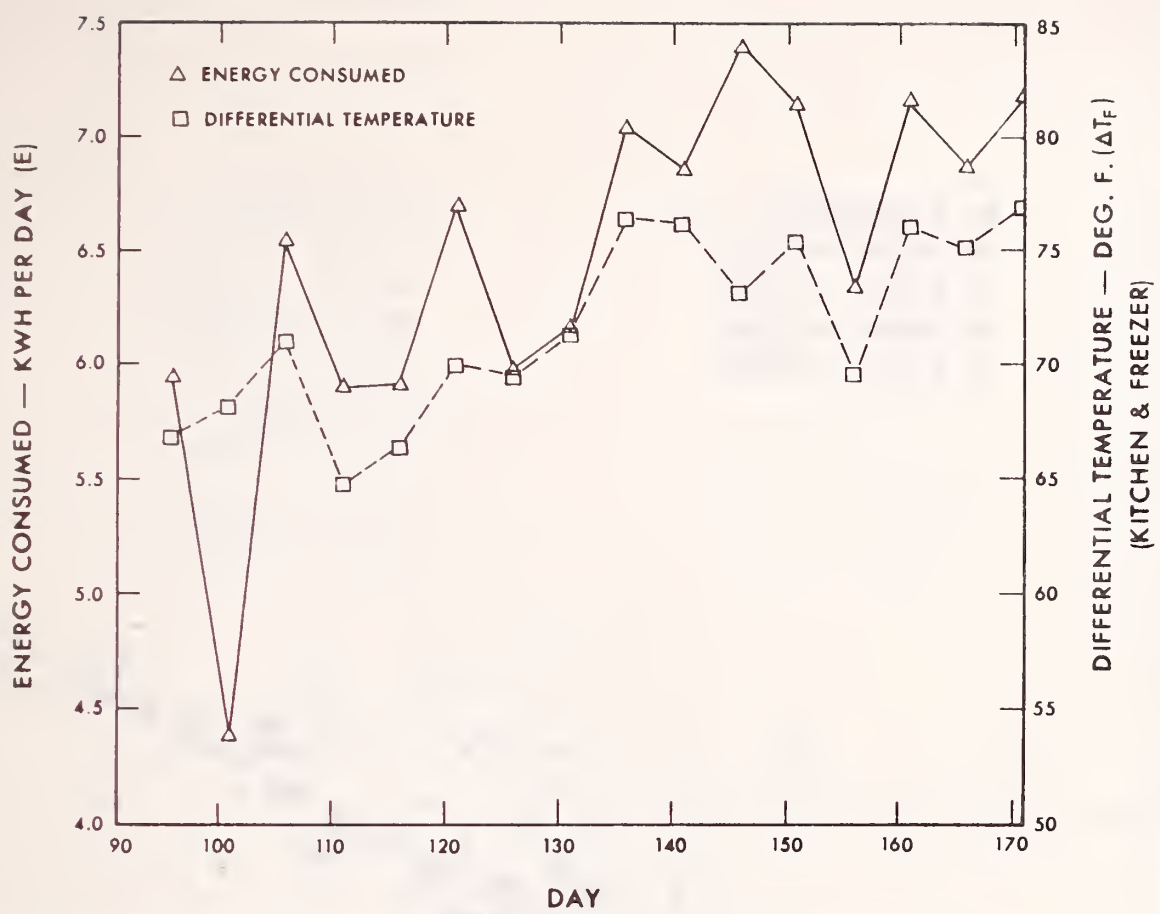
Figure 19   Energy Consumption and Differential Temperature versus Days
for Refrigerator   (Townhouse 8)
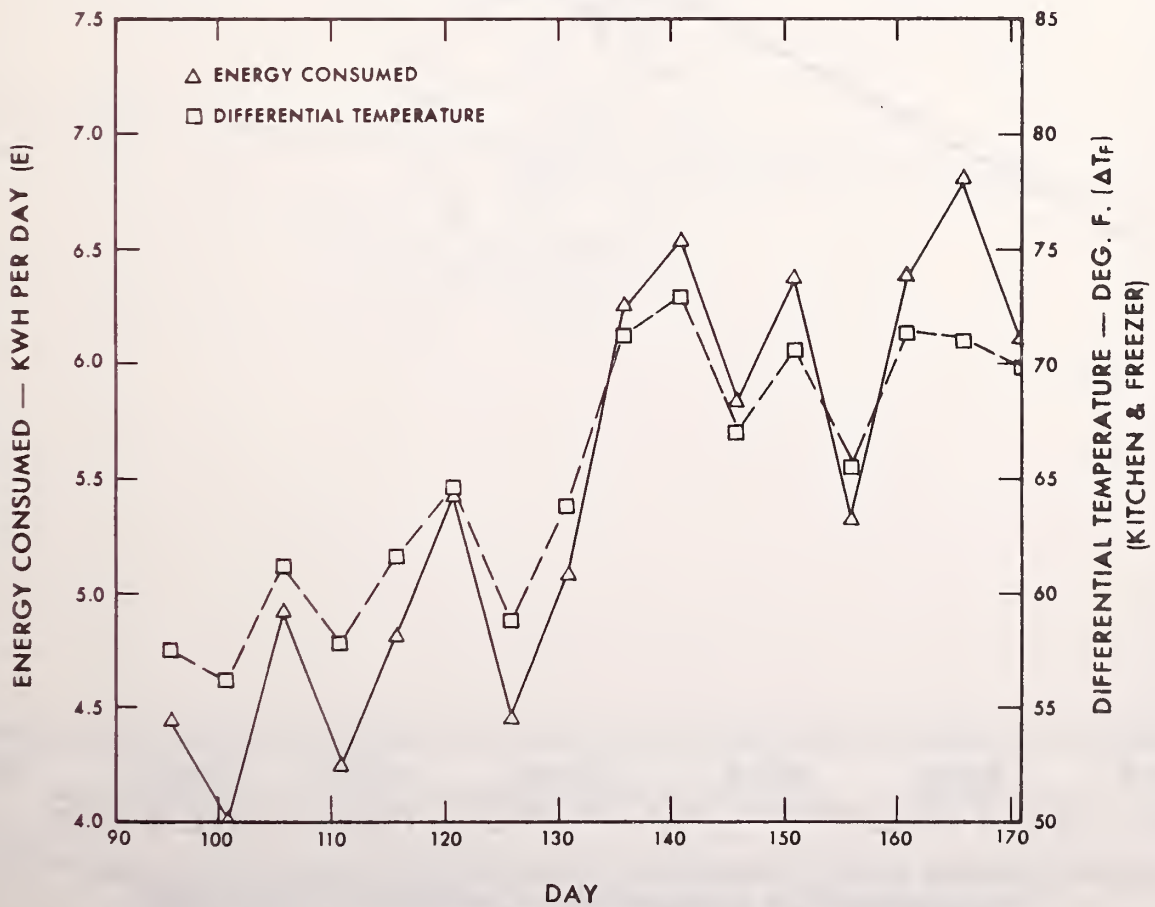
Figure 20   Energy Consumption and Differential Temperature versus Days
for Refrigerator (Townhouse 7)

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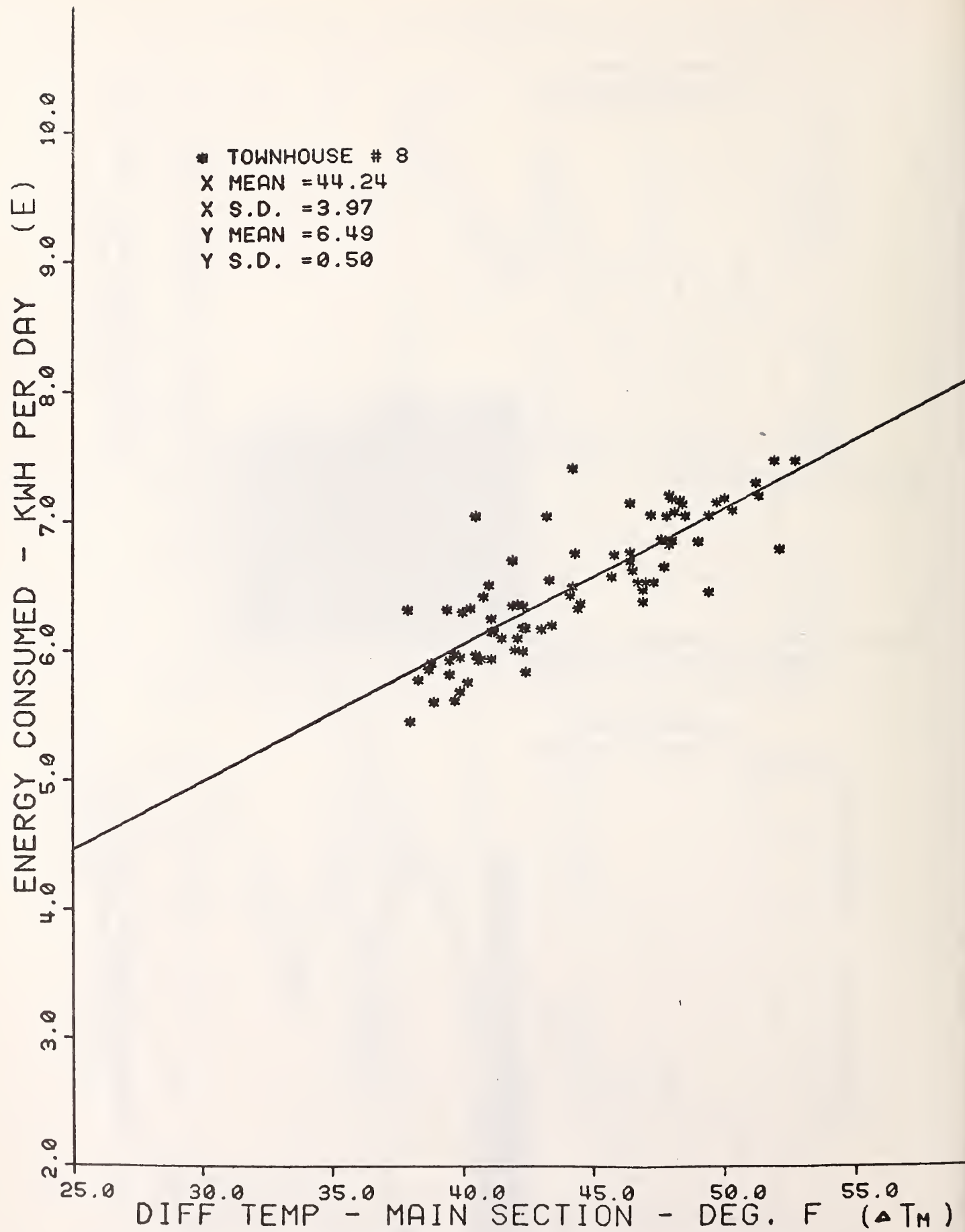
Figure 21   Daily Energy Consumption versus Main Section Differential
Temperature for Refrigerator (Townhouse 8, days 96-180)
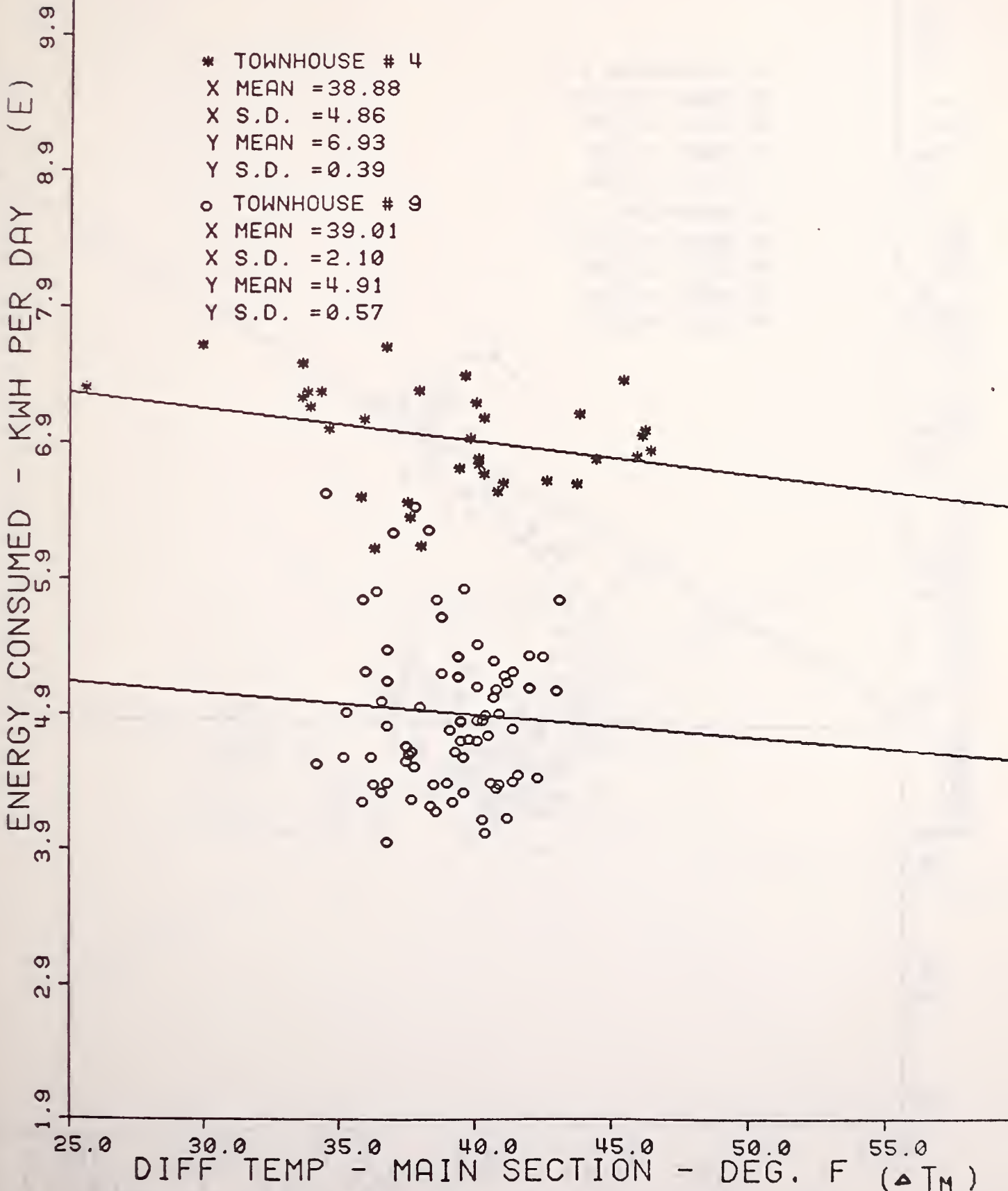
Figure 22   Lack of Correlation Between Refrigerator Energy Consumption and
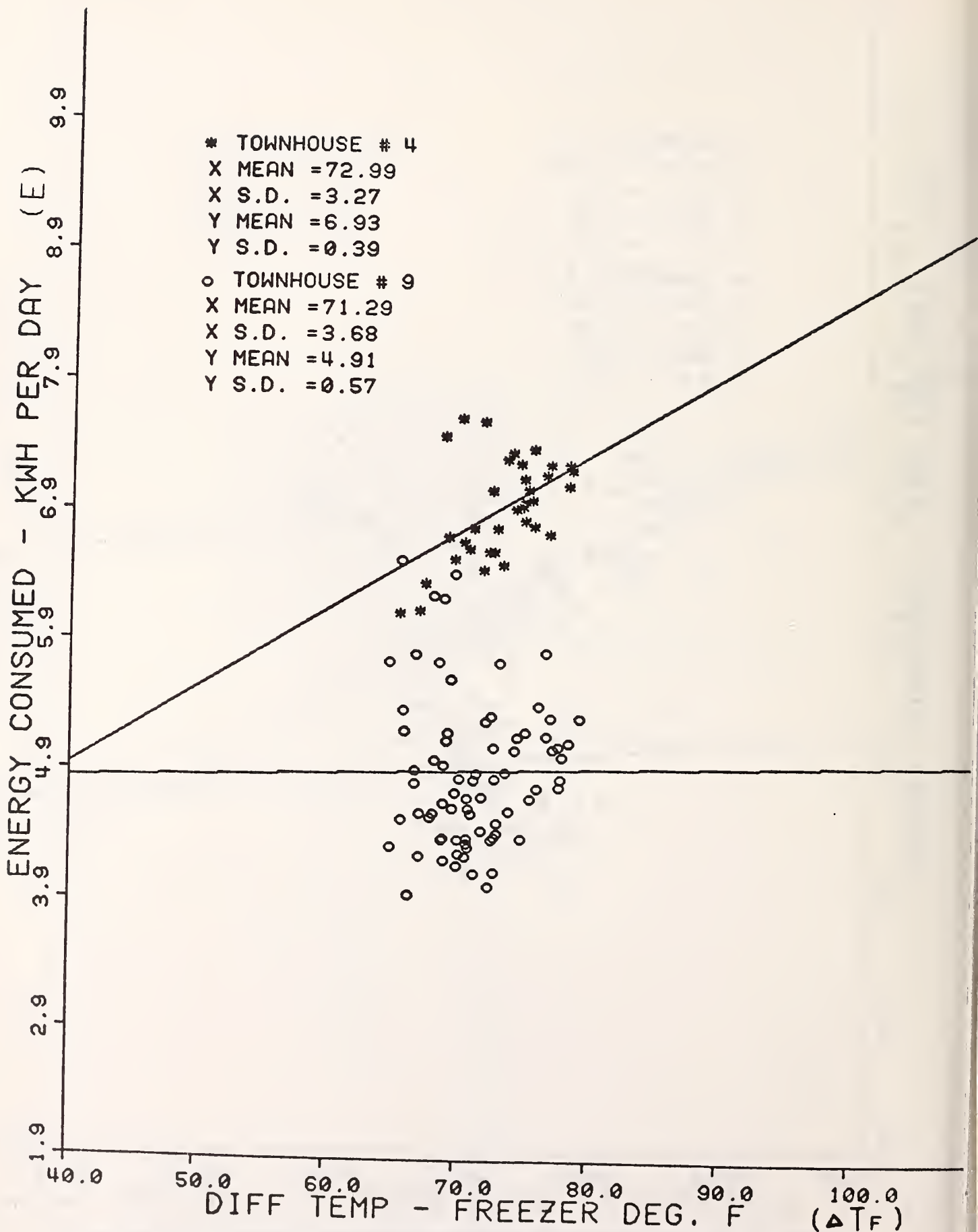Main Section Differential Temperature (Townhouses 4 and 9,
days 92-174)

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Figure 23 Differential in Correlation in Energy Consumption and Differential
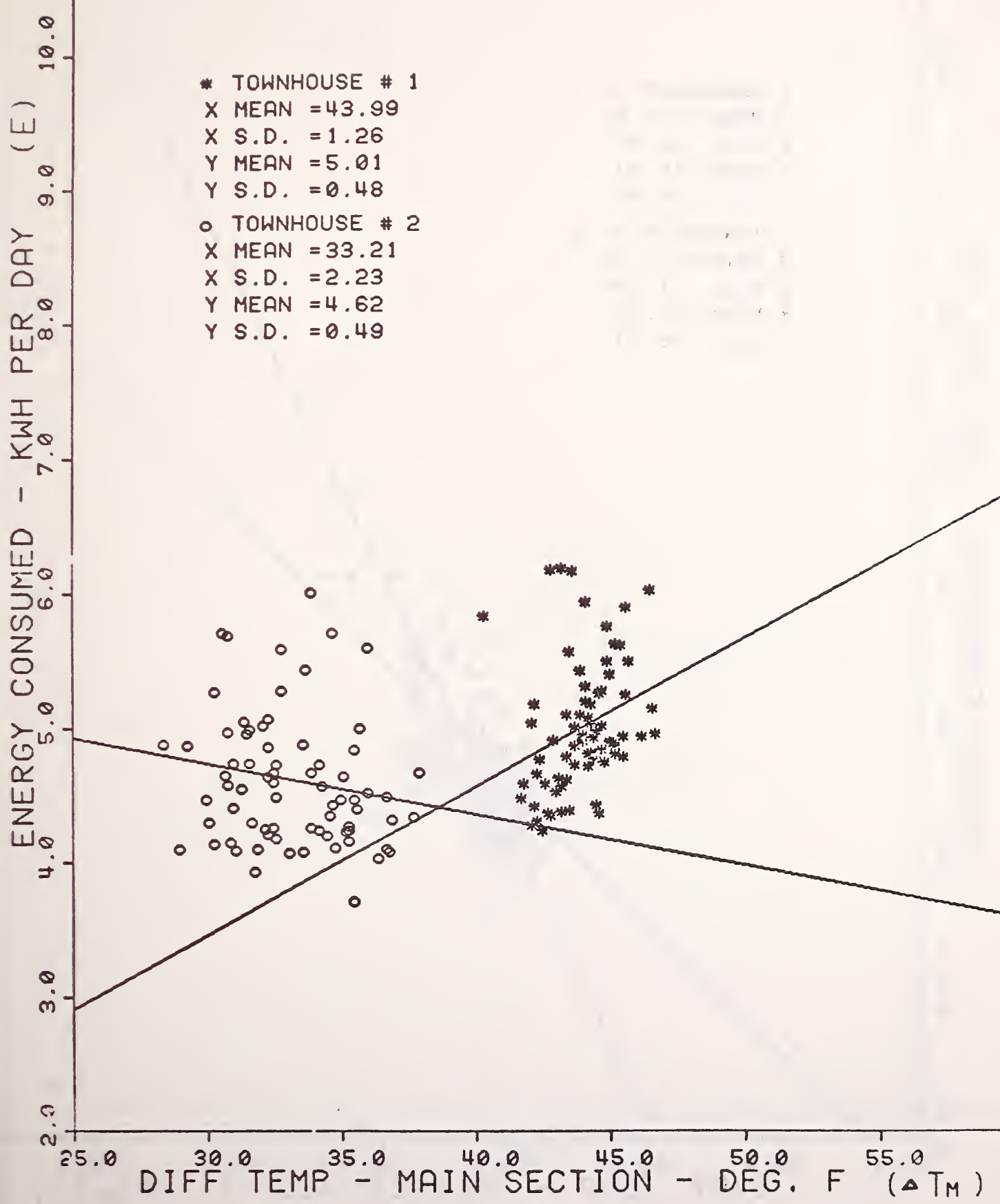Temperature of Freezer Section (Townhouses 4 and 9)

Figure 24   Energy Consumption versus Differential Temperature of Main
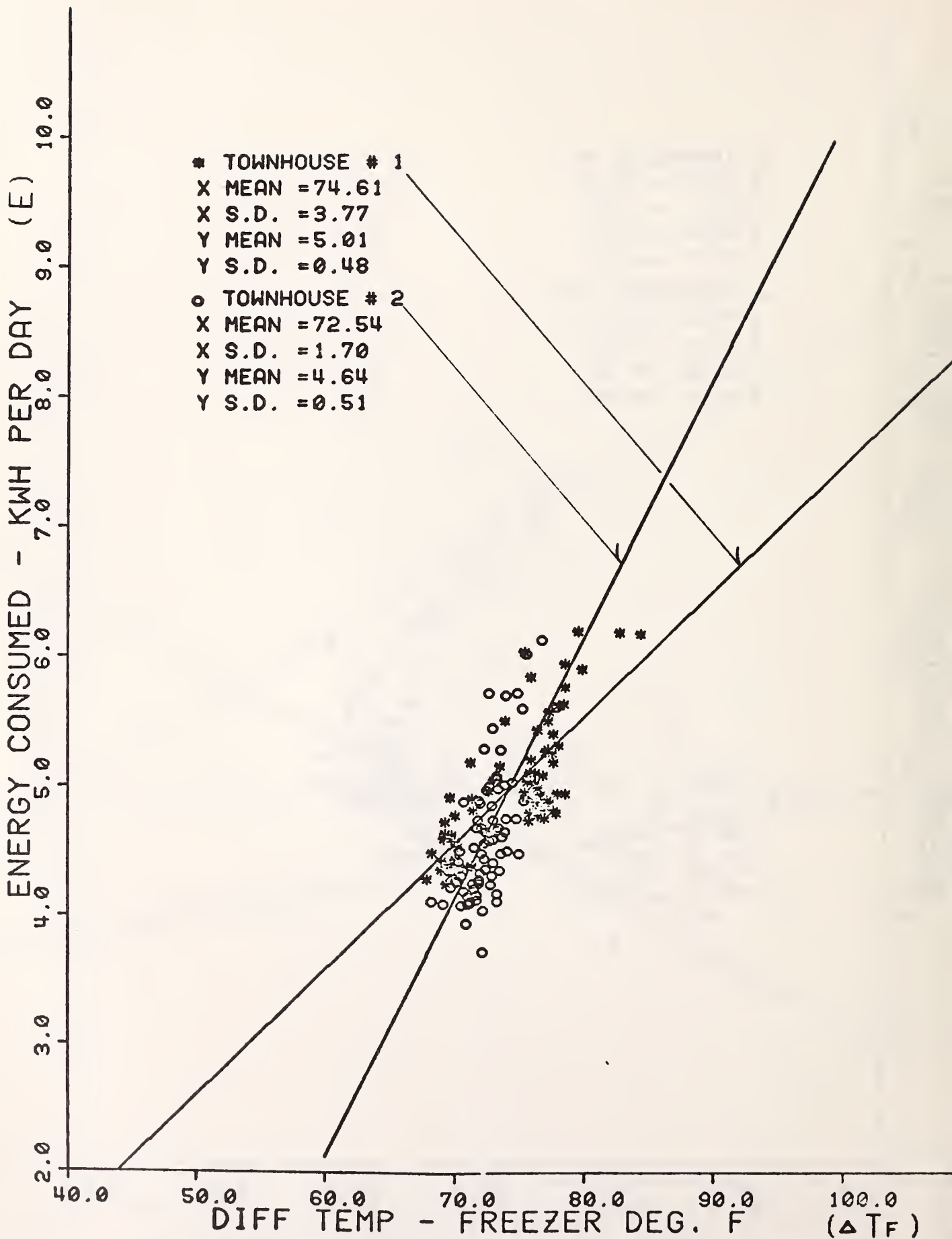Section for Refrigerator (Townhouses 1 and 2, days 167-249)

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Figure 25   Energy Consumption versus Differential Temperature of Freezer
Section for Refrigerator (Townhouses 1 and 2, days 167-249)
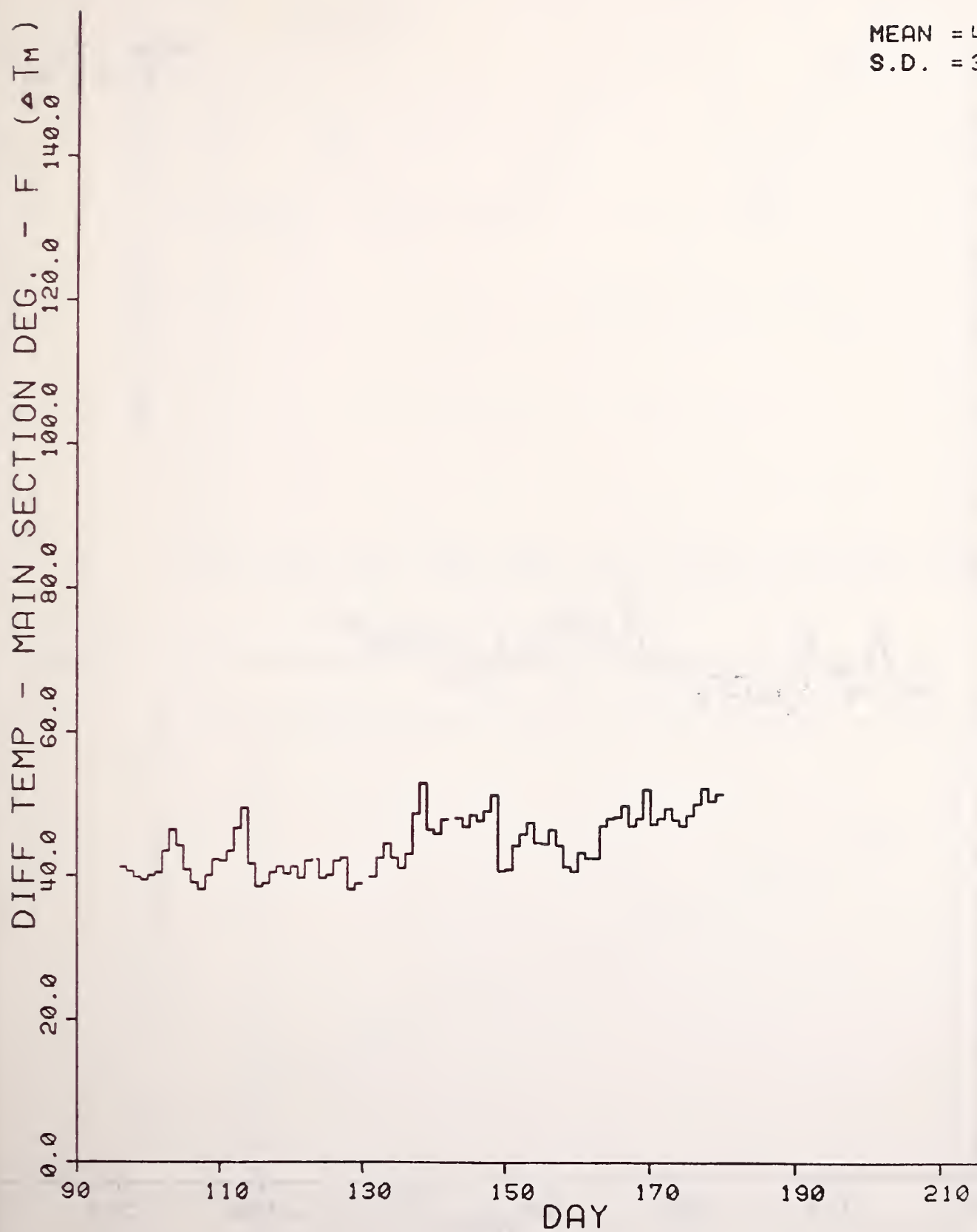
Figure 26   Daily Average Differential Temperature of Main Section versus
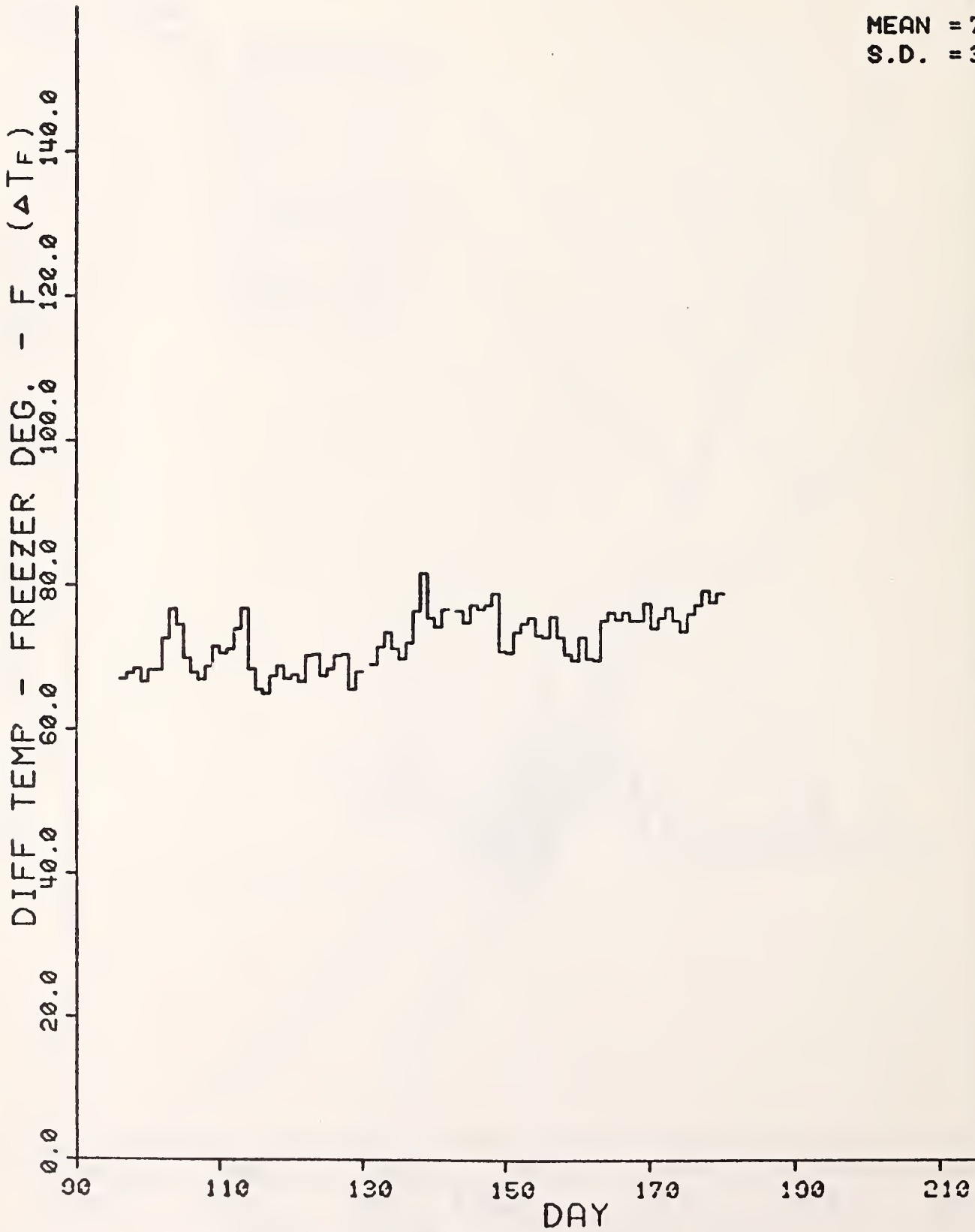Days for Refrigerator (Townhouse 8)

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Figure 27   Daily Average Differential Temperatures of Freezer Section versus
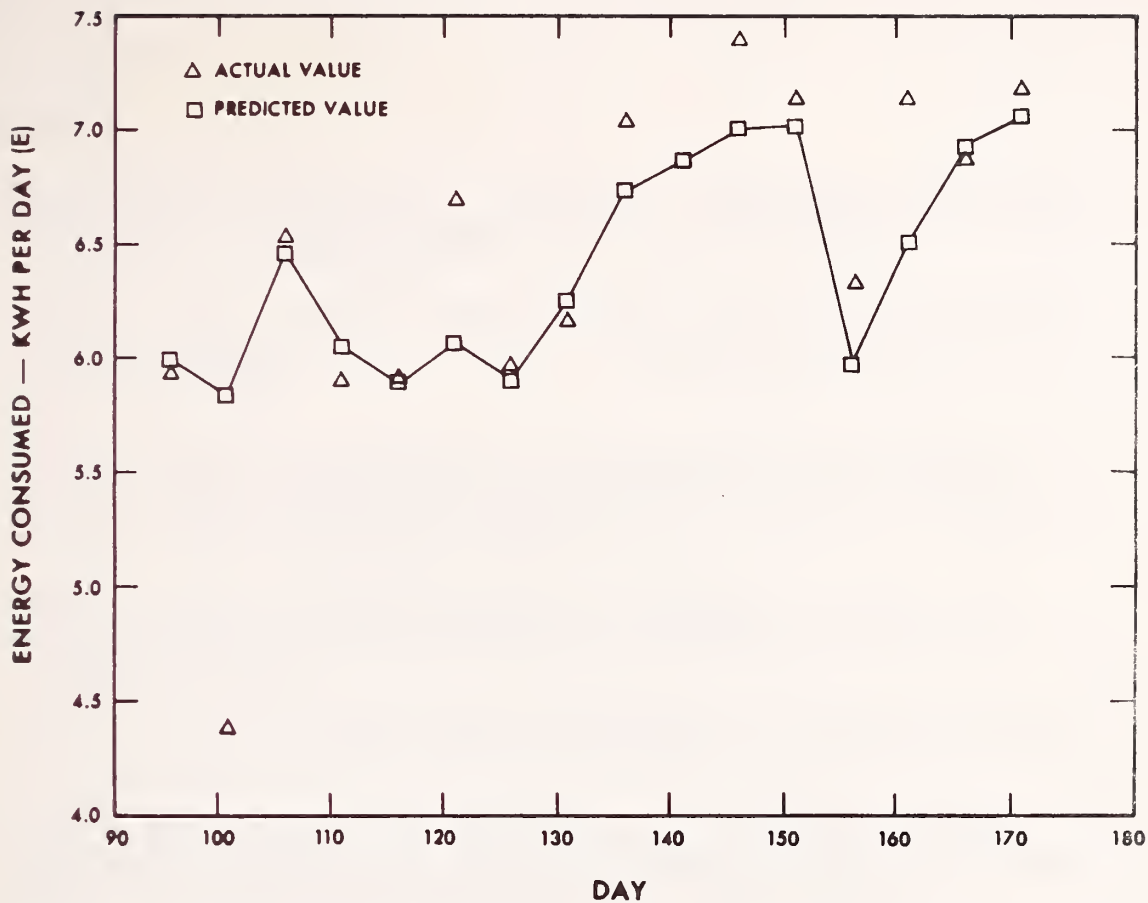Days (Townhouse 8)

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Figure 28 Actual and Predicted Refrigerator Energy Consumption (Townhouse 8)

PHYSICAL SIZE OF REFRIGERATOR - CU.FT.
MODEL--LINEAR--E=A0+A1×V
FROST-FREE MODELS ONLY

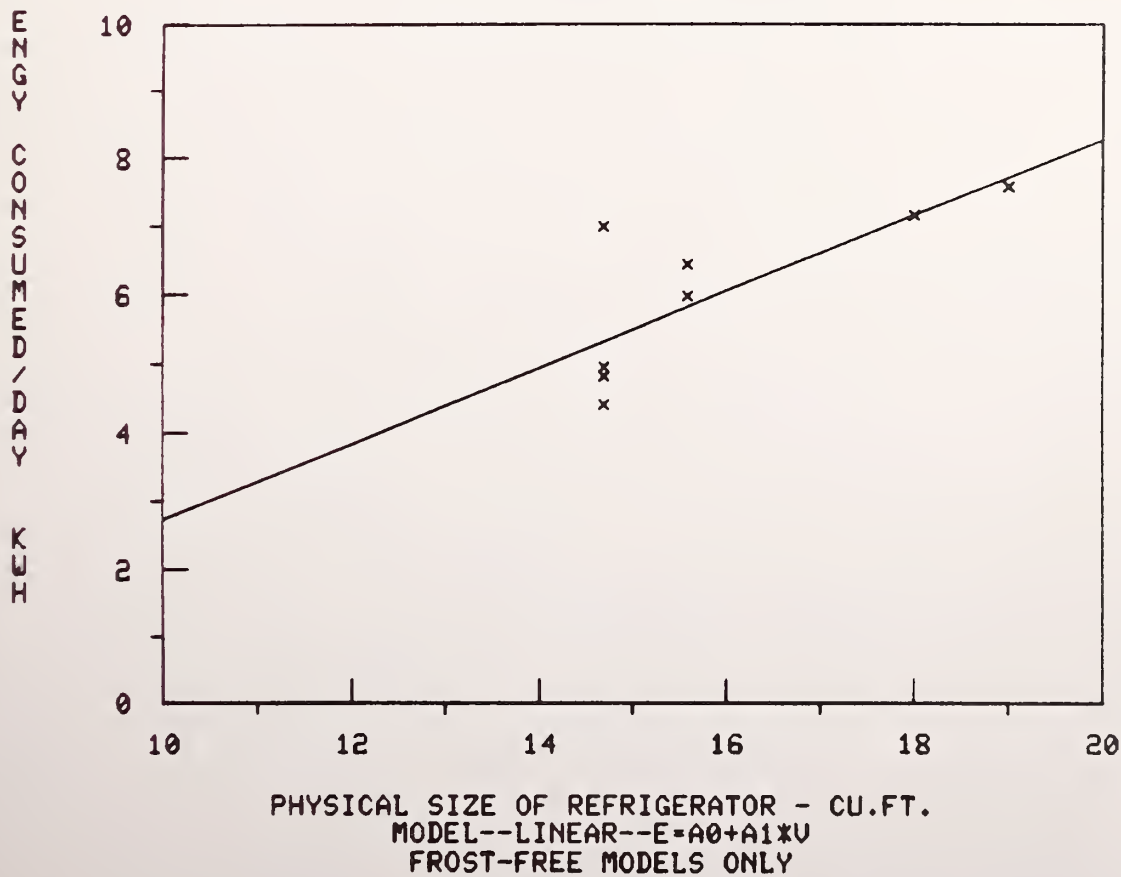Figure 29 Energy Consumption of Refrigerator vs. Refrigerator Size

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U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 79-1781	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE FIELD PERFORMANCE OF RESIDENTIAL REFRIGERATORS AND COMBINATION REFRIGERATOR-FREEZERS	5. Publication Date July 1979
	6. Performing Organization Code

7. AUTHOR(S) Yui-May Chang and Richard A. Grot	8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, DC 20234	10. Project/Task/Work Unit No. 742 2500
	11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)	13. Type of Report & Period Covered
15. Supplementary notes	14. Sponsoring Agency Code

16. ABSTRACT

Evaluation of the performance of household refrigerators and combination refrigerator-freezers was undertaken in a field experiment to determine the effect of room environment and occupant-usage habits on energy consumption of these appliances. This report presents the results of such an experiment in ten townhouses at Twin Rivers, N.J. One-door manual defrost and two-door frost-free models of various sizes were studied. Energy consumption, kitchen temperature, refrigerator temperature and door openings were measured for each model by data acquisition systems located in the townhouse basements. Both daily and hourly averages and variations about the average for each variable were calculated to determine occupant-usage patterns.

Statistical techniques were utilized to obtain the effect of parameters on energy consumption of these appliances by linear regression of both one- and two-parameter models.

It was found that for a given model the temperature difference between the kitchen and the refrigerator (either main or freezer section) had the most effect on energy consumption, with a lesser, though still important, contribution from the door openings.

In addition, the normalized energy consumption of each model, in different combinations of variables, was calculated from its regression coefficients and the overall average values of parameters from the measurements. The results of these normalized values turned out to be within 5%. Therefore, their mean values could be considered as the typical energy consumption for each refrigerator or combination, under usage conditions.

The linear relationship among the combination refrigerator-freezers according to their physical sizes indicated an increase of about 0.55 kWh per day for each additional cubic foot increase in volume. Energy conservation by using a manual-defrost refrigerator was predicted at approximately 40% from the available measurements and other related laboratory test results.

17. Key Words: Combination refrigerator-freezer field data; daily load profiles; energy consumption; field measurements; hourly load profiles; refrigerator field data; usage profiles.

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